nature portfolio

Peer Review File

Broadband generation and tomography of non-Gaussian states for ultra-fast optical quantum processors

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors present an experimental scheme to achieve high-frequency generation and detection of non-Gaussian optical quantum states, based on photon subtraction from squeezed vacuum.

Compared to more traditional schemes based on CW lasers, where the squeezed vacuum is generated in an OPO, whose bandwidth mainly determines the maximum rate of non-Gaussian state production after heralding, here an OPA is used, followed by a second parametric crystal acting as a phase-sensitive amplifier. The high bandwidth of the system is thus preserved until the final homodyne detection stage, where a fast commercial amplifier is used. The only constraint to a very high GHz-level bandwidth is given by the timing jitter of the single photon detector adopted in the experiment, but the authors envision future improvements based on recently-proposed theoretical schemes using further OPAs to overcome the current limits.

I find the manuscript very interesting and probably worth publishing, but I have a few concerns that need to be fully addressed by the authors in a revised version before making up my mind.

- In the introductory part at page 4, the generation of Gaussian and non-Gaussian states is described in a rather confusing way, first talking about squeezed light (Gaussian), then saying that the rate of non-Gaussian state generation is of kHz-order. Then again, citing the 43 GHz record in the generation and detection of (Gaussian) squeezed states thanks to the use of a PSA.
Also, the authors talk about three orders of magnitude improvement of the rate in the abstract, and two orders of magnitude in the text. They should make up their mind and clearly state which are the previous results they are comparing to. For example, in [8] it seems that the maximum rate for generating kitten states was up to 174.3 kcps, while already in 2009 heralded single photons (another clearly non-Gaussian state) had been produced and detected at rates in the hundred of kHz-range (Optics Letters 34, 2739 (2009)). The rate improvement demonstrated here would thus not even be one order of magnitude, significantly lower than what the authors claim in the abstract.

If this is indeed the case, I am afraid that there is not much novelty in this manuscript from a quantitative point of view to grant publication in Nature Communications, unless the authors provide some more convincing arguments to support their claims.

What I find more interesting and worth stressing more clearly is rather the qualitative step forward of the first (if I understand correctly, but the authors should clearly justify this, in case) application of the parametric amplification step as a PSA to homodyne detection and measurement of non-Gaussian quantum states at high bandwidth.

- One fundamental ingredient of this experiment is the PSA that allows the authors to preserve the high bandwidth of the system also in the detection stage. Given its importance and rather recent introduction in the field, I would really like to see many more details about its role and working principles, together with some more technical explanations about its operation. In the current version, too many aspects of the operation of the PSA are just given for granted, but the reader should not be forced to guess or read all the previous literature to understand it. For example, it is not explained how the different state quadratures are selected and measured. How is the phase of the PSA locked to the desired quadrature? Is the phase of the LO also scanned, or is it kept fixed?

- I do not agree with the naming of the heralding and detected modes as “idler” and “signal” modes, respectively. Since we are dealing with completely degenerate PDC, there are no distinct “signal” and “idler” modes in this case. One could instead refer to the portion of the down-converted beam that is split off as the “herald” mode, or something equivalent.

- I think it would be important to correctly identify (brand name and model) at least the main experimental pieces of equipment used for these measurements: laser, crystal waveguides, SNSPD, homodyne detector, amplifiers, oscilloscope, etc.

- Are the reconstructed Wigner functions of Fig.4 obtained from raw data or by correcting for some amount of detection inefficiency in the maxlik algorithm?

- One minor, but nevertheless important point is the poor English of the text, which certainly needs some additional spell-checking and probably also some revision by a mother-language reader. At the moment, the manuscript is not written too well and there are several typos scattered around the text that make it difficult to read.

- Finally, I am also a bit concerned by the ratio of self-to-other citations in the manuscript, which appears rather unfairly balanced at the moment.

Reviewer #2

(Remarks to the Author)
The authors report the high-rate generation and tomography of non-Gaussian quantum states, up to the MHz range, and present their results as a breakthrough in the field. They notably write several times that “the current generation rate of the non-Gaussian states remains on the kHz order” and that their results are therefore “almost three orders of magnitude higher than the current state-of-the-art experiments”. But this concept of “generation rate of the non-Gaussian states” is misleading, as the generation rate depends on the complexity of the considered non-Gaussian states. For instance, high-rate generation and tomography of single-photon states was already performed in [M. Cooper et al., Opt. Express 21, 5309–5317, 2013], reaching 180kHz. This remark is important as the states generated in the present paper are photon-subtracted squeezed vacuum, which are nothing else than squeezed single photon states, also called “kitten” states (see for instance refs [27, 29]): Such states could also be obtained by sending single-photon states to the same kind of Phase Sensitive Amplifier (PSA) as the one used in this work to perform state tomography. It is therefore relevant to compare the performances of the present experiment with single-photon experiments like Cooper’s one. The generation rate obtained in the present paper is therefore at most five times higher than previous results, not three orders of magnitude.

The authors also assert that “The performance is constrained only by the superconducting detector’s jitter which currently limits the usable bandwidth of the squeezed light to 1 GHz, rather than the optical and electronic systems”. This is questionable for several reasons. Let us first note that the jitter of their detector is 130ps, what is quite good for electronics: it will be really difficult to do better, even with another detector. But the main point is that a drop of the Wigner’s function negativity is observed at the highest generation rates. The reported negativity is indeed about -0.09 up to 310kHz, but drop to -0.066 at the highest rate of 900kHz. These results are obtained for the same bandwidth of 1GHz of the squeezed light, the only difference being the pump power. It therefore seems that there are other factors that limits the generation rate. Furthermore, even negativities of -0.09 are not so good compared to previous results from some of the authors in reference [7]. The fidelities to the theoretically expected states should have been presented and discussed. Here the authors present the fidelity of the states with additional losses after the PSA to the state without losses, not to the theoretically expected state...

To conclude, the authors present a setup whose main originality is a high bandwidth homodyne detection thanks to a Phase Sensitive Amplifier (PSA). This system was already presented by the authors in reference [12] and assessed with squeezed vacuum (including for what concerns added losses after the PSA). The only difference of the present work is the heralding part introduced to perform the photon subtraction and generate a non-Gaussian state. This is certainly an important step for the authors, but not a major breakthrough for the community. Furthermore, the quality of the generated states is not so high compared to the state-of-art in the CW regime, and the reasons of this should be discussed. I therefore think that, if this work certainly corresponds to a scientific step and should be published somewhere, it does not deserve publication in a high impact journal as Nature Communications.

Reviewer #3

(Remarks to the Author)
In this article, an experimental generation of high-speed non-Gaussian quantum state at a telecom wavelength is demonstrated. The generation scheme is based on the application of a non-Gaussian operation (photon subtraction) on an initial Gaussian quantum state (squeezed vacuum state).

At first, the squeezed vacuum state is produced using a broadband Optical Parametric Amplifier (OPA). Then, a photon subtraction operation is performed using a combination of half-waveplate, spectral filters and a single photon detector. Finally, the produced non-Gaussian state is measured using a broadband homodyne detection scheme based on Phase Sensitive Amplifier (PSA).

In this experimental work, non-Gaussian quantum state generation at a rate of 0.9 MHz is demonstrated, limited by the timing jitter of the single photon detector.

I think this work is timely given the increasing interest in doing CV universal quantum information processing. Even though the generation speed in this work can be reached using the state-of-the-art experimental demonstrations, the authors claim to be able to produce non-Gaussian quantum states with a speed up to 66 GHz, which may have a significant impact for efficient quantum computation tasks using better single photon detection strategies, and thus, drive me to recommend it for publication.

Before the paper can be published though, I believe that several points should be addressed:

1- At first, I think that the authors have to improve the writing. In this manuscript, I find a lot of repetitions and not well written sentences (for example, the first sentence in page 9, the before last sentence in page 11, the third sentence in the second paragraph of page 15…etc). Also, upper case letters are used to name the systems in figure 2 but referenced in the text using lower case letters.
2- I think that some other references can be added in this manuscript. As an example, in the last paragraph of page 4, The authors mentioned the fact that multiple-step interference of non-Gaussian states is needed to produce GKP codes. I think that the authors can add some state-of-the-art proposals for GKP state production such as the one given in [Quantum Sci. Technol. 8, 025007 (2023)] for single-stage multi-inputs multiplexed interference scheme, and in [PRA 109.2, 023717 (2024)] for boson sampler-based scheme. Also, in the Data acquisition and analysis section, the reference [PRA 96.5, 052304 (2017)] can be added for the temporal wave-packet of the produced non-Gaussian state.
3- The authors claim to produce high speed non-Gaussian quantum states for efficient quantum information processing using continuous variable (CV) encoding. The main speed limitation in their demonstration is caused by the timing jitter of the heralding detectors. However, I think that with discrete variable (DV) encoding, a much higher speed can be reached with the state-of-the-art technology. In this regard, I think that the authors have to address this point in the introduction to motivate the choice of CV instead of DV-based quantum processor.
4- The authors mentioned that they used a cascade of three filters in the heralding path, which gives an overall heralding efficiency of 15%. However, they didn’t give any motivation on why they used three different filters. By using the one of 1GHz, they can increase the heralding efficiency and thus increase the generation rate. I think that they have to address this point in the paper.
5- I think that the authors can try other solutions to increase the generation rate in their experimental setup. As an example, they can increase the tapping ration with the half waveplate and the PBS to increase the count rate on the single photon detection. In addition, they can use temporal multiplexing of several single photon detectors in the heralding path to overcome the timing jitter limitation.
6- As a final comment, I think that the authors have to give more details to motivate the use of an additional low pass filter with 5 GHz bandwidth in the homodyne detection stage.

In short, I believe there are several points where some improvement is needed, but after that I think the paper is fit for publication in Nature communications.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have satisfactorily answered to most of my questions and have modified the manuscript in the correct directions, adjusting their claims and better explaining the different unclear parts.
I believe that the revised manuscript is now publishable in Nature Communications.

Reviewer #2

(Remarks to the Author)
The main novelty of the present work is the tomography of non-Gaussian states with a high-bandwidth commercial homodyne detection using a PSA. The point is that the authors already presented this detection system for the measurement of Gaussian (squeezed) states, and that its application to non-Gaussian states does not appear as very disruptive. The authors argue in their response that “verifying non-Gaussian states requires careful measurement of the whole distribution of the quadrature values in many different phases”, and that the tomography of non-Gaussian states is more sensitive to noises. These assertions could be commented by noticing that the characterization of Gaussian squeezed vacuum performed in ref [12] ([20] in the new manuscript) already required measurements of quadrature values for different phases (squeezed and anti-squeezed phases): the difficulty is to be able to fix the phase, but then measuring 2 phases or measuring a higher number of phases is of the same difficulty. Furthermore, the observed squeezing levels are quite good, witnessing good performances in terms of signal to noise ratio.

In fact, the main issue with non-Gaussian heralded states is the selection of the temporal mode and the calculation of the measured quadrature through equation (5) (which seems to be post-processed and not easily manageable in real-time at a GHz rate), together with the synchronization required to perform this integration and the related jitter issue. The jitter issue is a major bottleneck in such an operation, and the authors declare to still have a problem with it up to now: they envision solutions for this, but they have not implemented these solutions for now. This is certainly a very technical issue, but technologies are at the heart of such experiments (The present work mainly relies on a high-bandwidth commercial homodyne detection and on a 256 GSa/s commercial oscilloscope).

To conclude my point, I will use two citations of the authors from their new manuscript. They wrote on page 6, second paragraph: “As an example, if we have a continuous-wave squeezed light source with 100 MHz bandwidth and success probability of 1%, the generation rate will be 1 MHz”. They then write page 7 last paragraph: “This is achieved by substituting the light source and homodyne system of sub-100-MHz bandwidth with our system of 66 GHz, which theoretically improves the rate by about 660 times”. And, at the end, they present a generation rate of about 1 MHz, which is above the state of the art, but does not exhibit a specific advantage of their detection system compared to current sub-100-MHz bandwidth systems. Therefore, from my point of view, this work is certainly interesting but is not at this stage a groundbreaking achievement. To clearly exhibit a groundbreaking achievement, the authors should present performances that are clearly not reachable by standard sub-100-MHz technologies, that is at least 10 MHz. For this reason, I therefore still think that, if this work certainly corresponds to a scientific step and should be published somewhere, it does not deserve publication in a high impact journal as Nature Communications.

Reviewer #3

(Remarks to the Author)
The authors have modified the title and the text of their manuscript to better clarify the contribution of their paper, which consists of developing a system for the generation and characterization of broadband non-Gaussian quantum states of light. This is in fact a very important step towards developing high-speed CV-based optical quantum processors. I appreciate the efforts made by the authors to improve the revised version of the manuscript and I find that they have provided satisfactory replies to all of my comments and therefore recommend the publication of this work in Nature Communications.

Dear editor and reviewer,

First, we thank the editor for managing our submission and the reviewers for reviewing our manuscript. Thanks to the reviewers ' comments, we believe that our revised manuscript has been further improved and is now suitable for publication.

Before going to point-by-point responses, we would like to recapture the novelty and importance of our work here. The natural carrier frequency determines the clock frequency of quantum computation. This means that optical systems have the capability to reach THz clock frequency as their carrier frequency is a few hundred terahertz, a few orders of magnitude larger than that of other physical systems. However, the generation of strong nonclassical states called non-Gaussian states has been limiting this as the generation rate is below MHz order. The base limitation comes from the bandwidth of the light source and measurement of the system, which has been limited to 100 MHz.

In our work, we elevate this bandwidth by developing a setup and technique for broadband generation and tomography of non-Gaussian states, where bandwidth can be up to 66 GHz. Although its usage is currently limited to 1 GHz due to the jitter of the superconducting photon number resolving detector, this issue can be resolved. Another important aspect, as pointed out by reviewer 1, is that our work is the first application of parametric amplification to homodyne detection and tomography of a non-Gaussian state. This is a crucial advance to achieve high-rate generation of non-Gaussian state; state generation using broadband components will only be meaningful if one can measure and verify the state.

In our original submission, the title and the introduction were mainly focused on the generation rate aspect. After reviewing the comments, we realized that although our work achieves a high generation rate, comparing generation rates across different past works is challenging. A fair comparison requires the states to have similar purity and fidelity among other parameters, as fidelity and purity can often be traded for generation rate in experimental setups.

Thus, a suitable comparison would be the system's bandwidth because if we have the same setup but with a broader bandwidth, the generation rate will be proportional to it. In the light of this, we modified the overall text to reflect this. Also, we modified the title to “Broadband non-Gaussian state generation and tomography for ultra-fast optical quantum processors” to better capture the essence of our work.

We have prepared a revised manuscript addressing the reviewers' comments. Below, we address each reviewer's comments and questions point-by-point. Separately, we also submit a red-lined version of the manuscript showing the revisions that have been made.

Reviewer 1

> The authors present an experimental scheme to achieve high-frequency generation and detection of non-Gaussian optical quantum states, based on photon subtraction from squeezed vacuum.
>
> Compared to more traditional schemes based on CW lasers, where the squeezed vacuum is generated in an OPO, whose bandwidth mainly determines the maximum rate of non-Gaussian state production after heralding, here an OPA is used, followed by a second parametric crystal acting as a phase-sensitive amplifier. The high bandwidth of the system is thus preserved until the final homodyne detection stage, where a fast commercial amplifier is used. The only constraint to a very high GHz-level bandwidth is given by the timing jitter of the single photon detector adopted in the experiment, but the authors envision future improvements based on recently-proposed theoretical schemes using further OPAs to overcome the current limits.
>
> I find the manuscript very interesting and probably worth publishing, but I have a few concerns that need to be fully addressed by the authors in a revised version before making up my mind.

We thank the viewer for summarizing our paper. We also appreciate that the reviewer found our paper interesting and believes it is worth publishing.

> - In the introductory part at page 4, the generation of Gaussian and non-Gaussian states is described in a rather confusing way, first talking about squeezed light (Gaussian), then saying that the rate of non-Gaussian state generation is of kHz-order. Then again, citing the 43 GHz record in the generation and detection of (Gaussian) squeezed states thanks to the use of a PSA. Also, the authors talk about three orders of magnitude improvement of the rate in the abstract, and two orders of magnitude in the text. They should make up their mind and clearly state which are the previous results they are comparing to. For example, in [8] it seems that the maximum rate for generating kitten states was up to 174.3 kcps, while already in 2009 heralded single photons (another clearly non-Gaussian state) had been produced and detected at rates in the hundred of kHz-range (Optics Letters 34, 2739 (2009)). The rate improvement demonstrated here would thus not even be one order of magnitude, significantly lower than what the authors claim in the abstract.

If this is indeed the case, I am afraid that there is not much novelty in this manuscript from a quantitative point of view to grant publication in Nature Communications, unless the authors provide some more convincing arguments to support their claims.

What I find more interesting and worth stressing more clearly is rather the qualitative step forward of the first (if I understand correctly, but the authors should clearly justify this, in case) application of the parametric amplification step as a PSA to homodyne detection and measurement of non-Gaussian quantum states at high bandwidth.

We thank the reviewer for pointing this out. We have rearranged the introductory part of the manuscript so that the description is more linear and direct. We also clarified the qualitative description regarding the generation rate to clarify which work we compare it to. After careful consideration, we found that a fair comparison of the generation rate itself is rather difficult, as one can always trade the quality of the state for the generation rate.
Hence, we shifted to comparing the system's bandwidth, as bandwidth ultimately limits generation rates and allows for fairer comparisons. Assuming all other parameters from previous experiments remain the same, increasing the bandwidth by N times will also increase the generation rate by N times. We also agree with the reviewer that rather than the generation rate, which also increases, the first application of PSA to homodyne measurement and tomography of non-Gaussian states is a big achievement of this work, and we have modified the introduction to state this explicitly. We also emphasize that the PSA not only provides increased bandwidth but also offers high loss tolerance for measurements, which is essential for measurement-based quantum computation.

- One fundamental ingredient of this experiment is the PSA that allows the authors to preserve the high bandwidth of the system also in the detection stage. Given its importance and rather recent introduction in the field, I would really like to see many more details about its role and working principles, together with some more technical explanations about its operation. In the current version, too many aspects of the operation of the PSA are just given for granted, but the reader should not be forced to guess or read all the previous literature to understand it. For example, it is not explained how the different state quadratures are selected and measured. How is the phase of the PSA locked to the desired quadrature? Is the phase of the LO also scanned, or is it kept fixed?

We thank the referee for their encouraging comment. We have added more details on it. For the current work, as we are working with a single-mode state, we keep the phase of the PSA and LO locking in the same direction while rotating the state. The phase of the PSA is determined by the relative phase between the input state and the pump. Although they have different frequencies, their relative phase can be properly determined because they are exactly twice the frequency. Fast phase modulation of the pump of the PSA will be crucial when we move from a single mode state and want to work with a multimode state, and we are working on the technique to do so experimentally.

> - I do not agree with the naming of the heralding and detected modes as "idler" and "signal" modes, respectively. Since we are dealing with completely degenerate PDC, there are no distinct "signal" and "idler" modes in this case. One could instead refer to the portion of the down-converted beam that is split off as the "herald" mode, or something equivalent.

We have modified the"idler" to "herald," as suggested.

> - I think it would be important to correctly identify (brand name and model) at least the main experimental pieces of equipment used for these measurements: laser, crystal waveguides, SNSPD, homodyne detector, amplifiers, oscilloscope, etc.

We added the model name and the brand name as applicable in the Method section.

> - Are the reconstructed Wigner functions of Fig.4 obtained from raw data or by correcting for some amount of detection inefficiency in the maxlik algorithm?

No correction for inefficiency is done at any step. We obtained the Wigner functions from the raw data by using the maxlik algorithm used in quantum state tomography for CV systems. We add the text clearly stating this in the figure label.

> - One minor, but nevertheless important point is the poor English of the text, which certainly needs some additional spell-checking and probably also some revision by a mother-language reader. At the moment, the manuscript is not written too well and there are several typos scattered around the text that make it difficult to read.

We thank the reviewer for pointing this out. We have proofread the manuscript and corrected the typos.

> - Finally, I am also a bit concerned by the ratio of self-to-other citations in the manuscript, which appears rather unfairly balanced at the moment.

We thank the reviewer for pointing this out and have added more citations to make it more balanced and diverse.

Reviewer 2

> The authors report the high-rate generation and tomography of non-Gaussian quantum states, up to the MHz range, and present their results as a breakthrough in the field. They notably write several times that "the current generation rate of the non-Gaussian states remains on the kHz order" and that their results are therefore "almost three orders of magnitude higher than the current state-of-the-art experiments". But this concept of "generation rate of the non-Gaussian states" is misleading, as the generation rate depends on the complexity of the considered non-Gaussian states. For instance, high-rate generation and tomography of single-photon states was already performed in [M. Cooper et al., Opt. Express 21, 5309–5317, 2013], reaching 180kHz. This remark is important as the states generated in the present paper are photon-subtracted squeezed vacuum, which are nothing else than squeezed single photon states, also called "kitten" states (see for instance refs [27, 29]): Such states could also be obtained by sending single-photon states to the same kind of Phase Sensitive Amplifier (PSA) as the one used in this work to perform state tomography. It is therefore relevant to compare the performances of the present experiment with single-photon experiments like Cooper's one. The generation rate obtained in the present paper is therefore at most five times higher than previous results, not three orders of magnitude.

We thank the reviewer for the summarization and the comments. As pointed out by the reviewer, the concept of generation rate can be complex as it is highly dependent on the target state, the photon detection efficiency, and so on. However, in the case that the exact same setup is replace with broadband component, it is clear that the generation rate will increase as the probability will stay the same while the number of trial (determined by the inverse of the bandwidth) increases. We do agree that fair quantitative comparisons could be difficult as explained in the response to reviewer 1, thus we have modified the manuscript to be clear of what we are comparing to. In addition, the paper mentioned by the reviewer is based on pulsed light, where our paper is based on continuous-wave laser. The term bandwidth in both regimes could refer to different things, so we have added the explanation for this. In particular, for non-Gaussian state generation, what is important in pulsed system is the repetition rate which cannot exceed the bandwidth of the homodyne detector if one were to correctly measure the quadrature values. Nevertheless, we respectfully disagree with the reviewer that squeezed single photon sending to PSA is a good comparison to the generation rate of the single photon state. Our PSA and homodyne detector is a single set of measurement apparatus rather than an operation on the state and can be applicable to *any arbitrary state*. Our experimental tools here are not intended to generate a squeezed single-photon state but rather demonstrate the generation and measurement of the broadband "phase-sensitive" quantum state. Unlike single-photon states, which are phase insensitive, measurement and operation on phase-sensitive states, even in narrowband, is much more challenging, making our work novel and an important step for the community. We have modified the manuscript, especially the introduction and the title, to convey this better.

> The authors also assert that "The performance is constrained only by the superconducting detector's jitter which currently limits the usable bandwidth of the squeezed light to 1 GHz, rather than the optical and electronic systems". This is questionable for several reasons. Let us first note that the jitter of their detector is 130ps, what is quite good for electronics: it will be really difficult to do better, even with another detector. But the main point is that a drop of the Wigner's function negativity is observed at the highest generation rates. The reported negativity is indeed about -0.09 up to 310kHz, but drop to -0.066 at the highest rate of 900kHz. These results are obtained for the same bandwidth of 1GHz of the squeezed light, the only difference being the pump power. It therefore seems that there are other factors that limits the generation rate. Furthermore, even negativities of -0.09 are not so good compared to previous results from some of the authors in reference [7]. The fidelities to the theoretically expected states should have been presented and discussed. Here the authors present the fidelity of the states with additional losses after the PSA to the state without losses, not to the theoretically expected state...

Indeed, 130 ps jitter is already quite good for electronic systems, but we plan to improve it further. Also, if we look at the cutting-edge SSPD, a 3-ps jitter system exists, meaning that lowering this jitter is physically achievable [Nat. Photonics 14 250 (2020).]. The drop in negativity is not evidence of the change in the rate but rather due to the change in the squeezing level, which affects the tolerance toward optical loss of the state and is irrelevant in this context. Regarding fidelity, the explanation of the reviewer would be correct if we want to evaluate how close the generated state is to the ideal target state. But, as we have mentioned in the main text, the point here is that we need to show that PSA indeed preserves quantum information by "correctly" converting the quadrature information into the classical signal. The precise way to show this is to show that the signal after PSA is tolerant to optical loss, i.e., it has the same information as when there is no loss. The fidelity between two states represents this, and this is the quantity of our interest since we are introducing this new technique for tomography in a broadband non-Gaussian state. We also understand that the fidelity of the generated state to the ideal state is also a quantity of interest, so we have added that value to the text as well.

> To conclude, the authors present a setup whose main originality is a high bandwidth homodyne detection thanks to a Phase Sensitive Amplifier (PSA). This system was already presented by the authors in reference [12] and assessed with squeezed vacuum (including for what concerns added losses after the PSA). The only difference of the present work is the heralding part introduced to perform the photon subtraction and generate a non-Gaussian state. This is certainly an important step for the authors, but not a major breakthrough for the community. Furthermore, the quality of the generated states is not so high compared to the state-of-art in the CW regime, and the reasons of this should be discussed. I therefore think that, if this work certainly corresponds to a scientific step and should be published somewhere, it does not deserve publication in a high impact journal as Nature Communications.

Regrettably, we disagree with the reviewer on this. Combining PSA with a non-Gaussian state is nontrivial. Although several works are done using PSA and Gaussian state, Gaussian state and non-Gaussian state are certainly different things, and it is not just a trivial combination of the previous works. Gaussian states are usually verified via only noise power, while verifying non-Gaussian states requires careful measurement of the whole distribution of the quadrature values in many different phases. This means that the technical requirement for non-Gaussian states is much higher. For instance, in the evaluation of the Gaussian state, the presence of noise only affects the value of the noise power, and while the nonlinearity of the PSA might change the value of noise power, we can still observe squeezing, albeit at lesser levels.

On the other hand, for non-Gaussian states, the effects of PSA nonlinearity are severe. The nonlinearity could distort the distribution, making the tomography process inaccurate and leads to loss in Wigner negativity – a crucial requirement for universal quantum computation and fault tolerance. These effects, while detrimental, are less severe when working with the Gaussian system. Thus, a demonstration that PSA and broadband homodyne can be used for quantum tomography toward the high-rate generation of a quantum state is a significant step. The quality of the generated state in this paper is actually much higher than the Reference [M. Cooper et al., Opt. Express 21, 5309–5317, 2013], the referee mentioned. Compared to our previous result, the reduction of the quality is mainly due to the additional coupling to the OPA, which we have now added the information in the main text. Note that improving the coupling technique is somewhat technical and can be overcome.

Also, we also have different opinions on the significance and breakthrough of this works for the community. In the quantum optics community, generations of multimode entanglement have seen many progress thanks to the multiplexing technique in various domains such as time (which our group mainly used), frequency, and spatial mode. Moreover, Gaussian components and squeezed states are also quite well developed. On the other hand, in terms of quantum computation, optical system is relatively behind than other systems. The main reason is that generating non-Gaussian states is more difficult in optical systems than the others due to the lack of natural nonlinearity that must be replaced with the heralding method. The main difficulty here lies in the fact that although generation of entanglement is deterministic and can be high speed, the generation of non-Gaussian states has been very slow, making integration of these two difficult. Also, a slower generation rate means that verification and tomography of complex quantum states is almost impossible due to technicality limitations. To overcome this problem, there are many approaches, such as trying to find optical nonlinearity that can work or finding a new approach for state preparation. Our work presents a much simpler solution: replacing the known method with broadband detection and broadband light source. For instance, compared to a typical 10-MHz system, if we use a 66-GHz system, the rate will be 6600 times without having to do anything else. This opens the possibility of generation and tomography of quantum states that have never been achieved due to the low generation rate preventing tomography. This is especially true for multiphoton quantum states essential in many quantum computation tasks. Therefore, establishing techniques for dealing with broadband non-Gaussian states opens the possibility of generating and verifying complex non-Gaussian states that have never been done before. We firmly believe this is a breakthrough for the community.

Reviewer 3

In this article, an experimental generation of high-speed non-Gaussian quantum state at a telecom wavelength is demonstrated. The generation scheme is based on the application of a non-Gaussian operation (photon subtraction) on an initial Gaussian quantum state (squeezed vacuum state).

At first, the squeezed vacuum state is produced using a broadband Optical Parametric Amplifier (OPA). Then, a photon subtraction operation is performed using a combination of half-waveplate, spectral filters and a single photon detector. Finally, the produced non-Gaussian state is measured using a broadband homodyne detection scheme based on Phase Sensitive Amplifier (PSA).

In this experimental work, non-Gaussian quantum state generation at a rate of 0.9 MHz is demonstrated, limited by the timing jitter of the single photon detector.

I think this work is timely given the increasing interest in doing CV universal quantum information processing. Even though the generation speed in this work can be reached using the state-of-the-art experimental demonstrations, the authors claim to be able to produce non-Gaussian quantum states with a speed up to 66 GHz, which may have a significant impact for efficient quantum computation tasks using better single photon detection strategies, and thus, drive me to recommend it for publication.

We thank the referee for the summarization and the recommendations for the publication in Nature Communications.

Before the paper can be published though, I believe that several points should be addressed:

6- At first, I think that the authors have to improve the writing. In this manuscript, I find a lot of repetitions and not well written sentences (for example, the first sentence in page 9, the before last sentence in page 11, the third sentence in the second paragraph of page 15…etc). Also, upper case letters are used to name the systems in figure 2 but referenced in the text using lower case letters.

We thank the referee for pointing out this. We have proofread our manuscript again, revised the repetitive sentences, and fixed the typos.

2- I think that some other references can be added in this manuscript. As an example, in the last paragraph of page 4, The authors mentioned the fact that multiple-step interference of non-Gaussian states is needed to produce GKP codes. I think that the authors can add some state-of-the-art proposals for GKP state production such as the one given in [Quantum Sci. Technol. 8, 025007 (2023)] for single-stage multi-inputs multiplexed interference scheme, and in [PRA 109.2, 023717 (2024)] for boson sampler-based scheme. Also, in the Data acquisition and analysis section, the reference [PRA 96.5, 052304 (2017)] can be added for the temporal wave-packet of the produced non-Gaussian state.

We appreciate the additional reference suggestions and have added them to the revised manuscript.

3- The authors claim to produce high speed non-Gaussian quantum states for efficient quantum information processing using continuous variable (CV) encoding. The main speed limitation in their demonstration is caused by the timing jitter of the heralding detectors. However, I think that with discrete variable (DV) encoding, a much higher speed can be reached with the state-of-the-art technology. In this regard, I think that the authors have to address this point in the introduction to motivate the choice of CV instead of DV-based quantum processor.

We thank the reviewer for pointing out this. We agree that motivating the reader why we choose CV instead of DV is crucial and have modified the sentence to do so. On the other hand, we partially disagree on the speed. In the optical DV quantum computation, the speed will also be limited by the timing jitter of the detector used in at the readout which is no different than the non-Gaussian state generation of CV. Note that for pulsed light, the speed corresponds to repetition rate rather than pulse width. Moreover, when dealing with DV processor, single-photon state is usually required which makes it much more difficult to increase the generation rate. This is because increasing the rate usually means there is more photon in the system that needs to be distinguished.

4- The authors mentioned that they used a cascade of three filters in the heralding path, which gives an overall heralding efficiency of 15%. However, they didn't give any motivation on why they used three different filters. By using the one of 1GHz, they can increase the heralding efficiency and thus increase the generation rate. I think that they have to address this point in the paper.

Here we need to cascade three of them because the filters we have does not have adequate extinction ratio for the region of interest. In fact, this is because from the very broad bandwidth of 6 THz, we have to select only 1 GHz which is 1/1000. The 1-GHz filter we have has the extinction ratio of 30 dB, which means that power-wise if we use only one of them the ratio between 1 GHz to the unwanted region will be about 1:6, corresponds to about 80% fake count. We have mentioned this in the method section.

5- I think that the authors can try other solutions to increase the generation rate in their experimental setup. As an example, they can increase the tapping ration with the half waveplate and the PBS to increase the count rate on the single photon detection. In addition, they can use temporal multiplexing of several single photon detectors in the heralding path to overcome the timing jitter limitation.

Although this is true that the rate can be increased, as we are using SNSPD as an ON/OFF detector in sthis work, we must tap small amounts of light to prevent the possibility of having multiphoton in the idler path. Moreover, as we have now added in the main text, increasing the bandwidth of the system will increase the fundamental baseline of the generation rate, which will be important for the future generation of complex quantum state.

> 6- As a final comment, I think that the authors have to give more details to motivate the use of an additional low pass filter with 5 GHz bandwidth in the homodyne detection stage.

We have added the reason for this in the paper. The main reason is that since we know the bandwidth of the generated state, the excess frequency bandwidth results in excess noise that could interfere with extraction of shape of the temporal mode function and quadrature values. We have added the explanation in the method section.

> In short, I believe there are several points where some improvement is needed, but after that I think the paper is fit for publication in Nature communications.

We would like to thank the referee again for the constructive comments and we believe that we have significantly improved the manuscript.

Editorial

- We have completed the policy checklist and move the data availability section to the appropriate place
- We have also modified, section structure, the citation style, and the figure label to comply with the style of Nature Communication.

Sincerely,

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