Peer Review File

Manuscript Title: Photonic chip-based continuous-travelling-wave parametric amplifier

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

The paper from Riemensberger et. al describes a continuous-wave pumped silicon nitride optical parametric amplifier, demonstrating 12dB gain (2dB net gain) using a pump power of 7W. Their main claim of novelty is the continuous-wave pump regime. To contextualize the work from Riemensberger et. al, two classifications of work are of relevance should be brought to the authors' attention.

a. One of the authors' main claims is that the amplifier uses a pump operating in the continuous-wave (CW) regime. On-chip CW-pumped parametric amplification has been achieved in several other work. See for example:

(i) Kwang Jo Lee, Francesca Parmigiani, Sheng Liu, Joseph Kakande, Periklis Petropoulos, Katia Gallo, and David Richardson, "Phase sensitive amplification based on quadratic cascading in a periodically poled lithium niobate waveguide," Opt. Express 17, 20393-20400 (2009) – Gain achieved = 0.5dB

(ii) Takeshi Umeki, Osamu Tadanaga, Atsushi Takada, and Masaki Asobe, "Phase sensitive degenerate parametric amplification using directly-bonded PPLN ridge waveguides," Opt. Express 19, 6326-6332 (2011). – 11dB gain, CW pump power = 300mW

(iii) Masaki Asobe, Takeshi Umeki, and Osamu Tadanaga, "Phase sensitive amplification with noise figure below the 3 dB quantum limit using CW pumped PPLN waveguide," Opt. Express 20, 13164-13172 (2012) – 19.2dB gain

(iv) Takeshi Umeki, Masaki Asobe, and Hirokazu Takenouchi, "In-line phase sensitive amplifier based on PPLN waveguides," Opt. Express 21, 12077-12084 (2013) – 11dB gain, CW pump power = 300mW

(v) Tadashi Kishimoto, Koji Inafune, Yoh Ogawa, Hironori Sasaki, and Hitoshi Murai, "Highly efficient phase-sensitive parametric gain in periodically poled $LiNbO_3$ ridge waveguide," Opt. Lett. 41, 1905-1908 (2016) – 18.6dB gain, CW pump power = 1.4W

(vi) T. Kishimoto, K. Inafune, Y. Ogawa, N. Sekine, H. Murai, and H. Sasaki, "Periodically Poled $LiNbO_3$ Ridge Waveguide with 21.9 dB Phase-Sensitive Gain by Optical Parametric Amplification," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017), paper W2A.12. – 21.9dB gain

b. Performance of continuous-wave pumped fiber-based optical parametric amplifiers. The authors describe the novelty of their work from the potential to replace fiber amplifiers. To assess this, it is useful to understand current state of the art, CW fiber-based parametric amplifiers, which provide high gains. See for example the following with parametric gain ranging from 16dB to 70dB:

(vii) M. E. Marhic, N. Kagi, T.-K. Chiang, and L. G. Kazovsky, "Broadband fiber optical parametric amplifiers," Opt. Lett. 21, 573-575 (1996) – 18dB Gain

(viii) W. Imajuku, A. Takada, and Y. Yamabayashi, "Low-noise amplification under the 3 dB noise figure in high-gain phase-sensitive fibre amplifier," Electron. Lett. 35, 1954–1955 (1999) – 16 dB Gain.

(ix) J. Hansryd and P. A. Andrekson, "Broad-band continuous-wave-pumped fiber optical parametric amplifier with 49-dB gain and wavelength-conversion efficiency," in IEEE Photonics Technology Letters, vol. 13, no. 3, pp. 194-196, Mar 2001, doi: 10.1109/68.914318. – 49dB Gain.

(x) T. Torounidis, P. A. Andrekson and B. -. Olsson, "Fiber-optical parametric amplifier with 70-dB gain," in IEEE Photonics Technology Letters, vol. 18, no. 10, pp. 1194-1196, May 2006, doi: 10.1109/LPT.2006.874714. – 70dB Gain (Ref. 49)

These two bodies of work provide useful yardsticks to assess the current traveling wave parametric amplifier reported by the authors. The authors demonstrate 12 dB internal gain and 2dB net gain considering all losses using a CW pump. However, the authors did not adequately contextualize their work with the aforementioned two bodies of work, especially the first.

It may be seen from the above, that CW-pumped parametric amplifiers in waveguides on a chip have been demonstrated as early as 2009, with gains as high as 21.9dB, reported by T. Kishimoto et. al. Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017) paper W2A.12). From this prior body of work, it might appear that the novelty in the current work is diminished. The authors should comment on this existing area of work.

To replace fiber-based parametric amplifiers, the demonstration either needs to show that their work is already as good as devices used for optical communication systems, or has the potential to reach that goal. Currently the gain achieved still falls short of fiber optic parametric amplifiers, or even erbium-doped fiber amplifiers. This can somewhat be overcome by systems experiments showing implementation of the amplifier. The waveguide losses demonstrated by the authors is very low and this is commendable. But can the performance of the amplifier reach the level of fiber optics when considering the loss-nonlinearity metrics in their waveguide amplifier vs. the fiber-based amplifiers? It is mentioned in the discussion that based on the 0.15dB/m material loss in silicon nitride demonstrated in Ref. 19, higher gain is possible perhaps similar to that described in Ref. 49. The 0.15dB/m loss looks like it is already achievable by the group. Is there a possibility that this material can be implemented for this work to achieve even higher gain?

The authors mainly compare their work with other demonstrations of parametric amplifiers using a pulsed pump. From this angle, it is seen from Supplementary Table 1 that the gain achieved in these prior work have much higher gain, with 50dB in Ref. 10 being achieved and higher off-chip gain of 20dB. Ref. 11 demonstrates off-chip gain of 25dB whereas work in amorphous silicon (Opt. Lett. 36, 552-554 (2011)) demonstrates off-chip gain of 6dB. The reader is left wondering if these waveguides could achieve better CW pumped parametric amplification than the silicon nitride waveguide (if for example the waveguides are lengthened and similar CW pump powers are used), considering the high gains achieved using much shorter devices. In the absence of comparable gain demonstrated in their devices, authors would need to perform an analysis of these prior work based on the loss, length, nonlinearity tradeoffs, although the best would be the demonstration of gain that is on par with some of these prior work. In addition, to replace Er-based amplifiers which can provide gain of 30dB or more, comparable gain would be needed.

Equations 1 and 2: Equation 2 currently incorporates only beta2 and beta4. Describe the dispersive lengths for various dispersion orders, beyond the fourth order. At what order of dispersion does the dispersive length far exceed the device length? Since the device is 2 m long in total, typically neglected orders of dispersion in integrated waveguides could become necessary to evaluate here.

The authors state, "Therefore, we achieve for the first time a net parametric gain of up to 2 dB on a photonic chip accounting for both the on-chip optical propagation loss and the fiber-chip-fiber coupling losses." – This statement is not true, because net parametric gain accounting for both coupling losses and on-chip propagation losses have also been achieved in Refs. 12, 16 and 17. In addition, Refs. (iii), (v) and (vi) in my earlier comment have also achieved net parametric gain exceeding 2dB using a continuous wave pump.

Figure 3 (a). This plot shows the spectrum of (i) the pump only, (ii) the pump + signal. The authors should also show the spectrum of the signal only, so that the increased amplitude in the signal level with the pump on can be observed. Typically when there is parametric gain, the amplitude of the signal will be shown to increase compared to when the pump is off. There are no measurements which show this. I understand that there is a figure showing the modulation of the signal measured using an oscilloscope, but those are in electrical units (photodetector), and a reader would not be able to derive the quantitative gain achieved from those measurements.

The figure in Supplementary Information (S2) which was measured using the maximum hold mode on the spectrum analyzer. In these, individual example spectra of the signal comparing pump on and off was also not shown. The authors should show a few of these example spectra, perhaps at the wavelength extremes within the range measured (eg. 1545nm and 1565nm), at the peak gain wavelength and a couple more wavelengths within the range. In addition, figure S2, being a measurement, should show the individual data points in the curve plotted, as opposed to just a line plot. How does the simulation result compare with the experimental result in figure S2? Is there any reason why the range outside of 1545nm and 1565nm was not characterized?

Figure 3 (a) measures the gain as a function of input power. At higher powers, the discrepancy with calculations increases. The authors should address this. What effects could be causing this deviation?

The main claim of the paper is continuous-wave pumping as opposed to pulsed pumping in other schemes. This is a good achievement. However, a more robust discussion on the tradeoffs between the different platforms is lacking. Supplementary table 1 shows different parameters and gain achieved. Gs is considerably higher in Refs. 6, 8, 10 and 14, The comparison with prior work on continuous-wave pumped optical parametric amplifiers (Refs above with gain as high as 21.9dB) is important to compare but not included.

Overall, I find the work from the authors interesting, but without sufficient contextualization with existing work. Considering the higher gains achieved in other demonstrations of CW pumped on-chip waveguide parametric amplifiers (21.9dB in Ref. (vi)), much higher gains in fiber optic parametric amplifiers (70dB in Ref. 49), and significantly higher gains in pulsed pumped waveguide amplifiers (50W in Ref. 10), a much more rigorous discussion and experiments which show better amplification performance in the traveling-wave silicon nitride waveguide amplifier are warranted.

Referee #2 (Remarks to the Author):

Since the editors asked me for a quick review due to another reviewer dropping out, I'm going to be brief:

I can say that it's (a) an extremely important, milestone result, and (b) very well-written, clear, and of high quality. I'd endorse publishing it as-is in Nature. It's one of the best papers I've read recently in integrated optics.

I'm not going to transmit any of the traditional trivial quibbles. Go forth and publish this!

Referee #3 (Remarks to the Author):

Dear Authors,
I'm happy for having had the possibility to review your paper. The reported results, in terms of low losses, parametric gain and device bandwidth are surely novel and relevant. The data are generally well presented, and the rationale is clear.

My main doubt with the present submission is that the general claims are a bit exaggerated with respect to the real novelty and improvement reported in the text. The results are surely interesting, but they are mainly technological optimization and not real breakthrough ideas.

I do not foresee a potential impact as wide as I would expect from a Nature article; for this reason I consider the paper more suitable for "Light: science & applications", than for "Nature".

Regarding the technical comments, I believe that the following points should in any case be addressed before publication in a journal:

• 1) It seems to me that one of the main improvements allowing the realization of such a component is the realization of a super low loss Silicon Nitride. It would be important to highlight which are the key steps in order to obtain so low losses.

• 2) In the conclusion you cite a material loss of 0.15 dB/m, which is much lower than the waveguide loss of 2.5dB/m. Although it is clear, to those working in the field, that it is already an extremely good value, it would be important to explain in the text which are the factors causing such an increase of the linear loss parameter.

• 3) I was quite surprised, while reading your paper, by the “relatively high” coupling losses of your chip, which are evaluated as 2.5 dB/cm. Generally systems using lensed fibers and inverse tapers can achieve insertion losses lower than 1 dB/facet. Can you please explain why you had so high losses?

• 4) Please clearly specify in the figure captions if the reported power levels (especially for the pump) are in the fiber or in the chip. It would be nice, to understand also the reproducibility of the system, what is the power of pump beam immediately after the EDFA.

• 5) It would be extremely helpful to show the supplementary table 1 directly in the main text, and to add some real FOM, e.g. giving the G_S or G_I divided by the square of the pump power, as the FWM process efficiency is quadratic on pump level. Please also add (eventually in the supplementary material) all the equations used as definition of the different FOM.

• 6) As a reference, although for several reasons they are not very suitable for these applications, it would be nice also to see the comparison with results based on PPLN waveguides.

• 7) How high should the pump power be to achieve at least transparency (i.e. on-chip gain=10dB) in case of a 1mW and a 10 mW signal?

• 8) Can you please comment on the possibilities to reduce the pump-power requirements? As far as I know, a system with more of 10W of CW pump being delivered to the chip is probably not going to be considered as very appealing for real world applications.

Author Rebuttals to Initial Comments:

Resubmission of our manuscript "Photonic integrated circuit based continuous-travelling-wave parametric amplifier"

Here we present a detailed answer to the review. Our replies are highlighted in blue, while the red text sections indicate additions to the manuscript.

Referee #1 (Remarks to the Author):

First of all, we would like to thank the referee for his comprehensive review, which helped us to improve our manuscript and expand our knowledge of the field. Below, we provide step-by-step comments on the concerns expressed and indicate the corresponding changes made to our work.

The paper from Riemensberger et. al describes a continuous-wave pumped silicon nitride optical parametric amplifier, demonstrating 12dB gain (2dB net gain) using a pump power of 7W. Their main claim of novelty is the continuous-wave pump regime.

We would like to emphasize that our novelty is not only the continuous-wave operation.

It is above all the ability to achieve CW (continuous wave) parametric gain in a photonic integrated circuit (PIC) platform. This is not merely an academic distinction: the PPLN waveguides, which are discussed below (which also achieved CW parametric gain using the Chi(2) second order nonlinearity), while giving excellent performance, are made via **diamond blade dicing**.

They **are not a photonic integrated circuit (PIC) platform as in our case.** One cannot create complex integrated photonic circuits, which can even be combined with further optical or electrical functionality. In fact, for the PPLN waveguides only straight waveguide can be made with bulk micro-machining, severely limited device complexity. Moreover, the process itself is not a wafer scale manufacturing process. PIC can be processed at the wafer level, in high volumes and are already commercially used in the case of silicon for data center interconnects. For example: the waveguides in PPLN have to be *serially produced* using the micro-machining methods.

In contrast, we use in our work Si_3N_4 photonic integrated circuits. Over the past decade, this has emerged as a next-generation platform, that in contrast to mature silicon photonics has key advantages. It has x10-x100 times lower loss than silicon, and due to the large bandgap does not suffer from two-photon absorption. It is these favorable properties that enable us to operate the devices as continuous-wave optical traveling wave parametric amplifiers. Other advantages of the PIC platform include CMOS compatibility, open and diverse foundry access. In addition, the Si3N4 PIC have been used to create numerous complex and entirely novel devices. **PIC platforms enable a wide range of applications and building blocks, and thus the parametric amplifiers could be integrated with further on-chip functionality, very different than micromachined PPL chips**. From linear splitters, AWG, high Q resonators to integration with further functionality such as piezoelectrics for tuning, etc.

Silicon nitride is de facto replacing silicon in high power and low loss applications, and significantly extends the possible application scenarios, particularly with respect to power and wavelength range. Moreover, novel device principles are possible such as soliton microcombs. Another milestone Si3N4 recently achieved are lasers that have phase noise on par with a fiber laser. These properties make Si3N4 the most successful platform other than silicon over the last decade. It has transitioned from academic research to industry within less than 10 years.

Achieving parametric gain in Si_3N_4 is therefore a key step as it enables to endow the platform with gain and could provide (given the low loss, compact form factor resulting from the tight confinement) a novel building block for future PIC based on Si_3N_4.

To contextualize the work from Riemensberger et. al, two classifications of work are of relevance should be brought to the authors' attention.

a. One of the authors' main claims is that the amplifier uses a pump operating in the continuous-wave (CW) regime.

On-chip CW-pumped parametric amplification has been achieved in several other work. See for example:

(i) Kwang Jo Lee, Francesca Parmigiani, Sheng Liu, Joseph Kakande, Periklis Petropoulos, Katia Gallo, and David Richardson, "Phase sensitive amplification based on quadratic cascading in a periodically poled lithium niobate waveguide," Opt. Express 17, 20393-20400 (2009) – Gain achieved = 0.5dB

(ii) Takeshi Umeki, Osamu Tadanaga, Atsushi Takada, and Masaki Asobe, "Phase sensitive degenerate parametric amplification using directly-bonded PPLN ridge waveguides," Opt. Express 19, 6326-6332 (2011). – 11dB gain, CW pump power = 300mW

(iii) Masaki Asobe, Takeshi Umeki, and Osamu Tadanaga, "Phase sensitive amplification with noise figure below the 3 dB quantum limit using CW pumped PPLN waveguide," Opt. Express 20, 13164-13172 (2012) – 19.2dB gain

(iv) Takeshi Umeki, Masaki Asobe, and Hirokazu Takenouchi, "In-line phase sensitive amplifier based on PPLN waveguides," Opt. Express 21, 12077-12084 (2013) – 11dB gain, CW pump power = 300mW

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(vi) T. Kishimoto, K. Inafune, Y. Ogawa, N. Sekine, H. Murai, and H. Sasaki, "Periodically Poled LiNbO3 Ridge Waveguide with 21.9 dB Phase-Sensitive Gain by Optical Parametric Amplification," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017), paper W2A.12. – 21.9dB gain

Reply: We thank the reviewer for pointing out the references. We admit that we limited our discussion to purely Chi(3). The reason for this choice was that all efforts to create **photonic integrated circuit based traveling wave parametric amplifiers** to date, have been focused on **third order nonlinear material** (i.e. using PIC based on silicon, silicon nitride, etc.).

We agree that the results of PPLN are encouraging. However, we would like to emphasize that all work referenced by the reviewer, is concerning **bulk micromachined PPLN waveguide**, that are **not a photonic integrated circuit technology**.

We regret that we did not properly cite the above pioneering work on PPLN based parametric amplification – some of the papers we were not aware of. We thank the reviewer for the very careful and extensive literature list. ***In our revised version we have now pointed out the pioneering work on bulk waveguide PPLN OPA and the significant gain that has been achieved.*** However, we would like to underline that our breakthrough is not affected by these works, which is to demonstrate a CW **photonic integrated circuit**

based traveling wave amplifier. As mentioned above, our work is focused on the SiN-based Chi(3) photonic integrated circuit platform.

While recently also Chi(2) (in particular Lithium Niobate based) integrated photonic circuits have emerged, these have ***not*** demonstrated our result: that of CW traveling wave parametric amplifier. Indeed in comparison to Si3N4 this platform is very immature, and not commercially available via a foundry, and also not processed in CMOS foundries, as the material is not a CMOS certified one.

Action taken: To better clarify the novelty, we have also adapted our title. From "Photonic chip-based…" to "Photonic integrated circuit based...", to emphasize the PIC platform. We also added discussion of mechanically diced PPLN waveguide technology in Abstract and Introduction.

Addition to Abstract: "In the optical domain, pioneering work demonstrated continuous wave (CW) net-gain travelling wave parametric amplification in fibers[6], enabling e.g. phase sensitive (i.e. noiseless) amplification[7], link span increase[8], signal regeneration, nonlinear phase noise mitigation and spectral cloning. Achieving such traveling wave parametric amplifiers in photonic integrated circuits, that are silicon wafer-scale manufacturable and can be integrated with a wide range of on-chip optical components, would benefit from their high nonlinearity [10–18], compact footprint, resilience to optical feedback, and ability to lithographically tune gain. Yet, on chip CW parametric amplification has not been attained with photonic integrated circuits, compounded by high waveguide propagation losses or insufficient interaction length. Despite major progress[10–18], all demonstrations of net parametric gain have necessitated pulsed lasers, limiting their practical use. To date, only bulk micro-machined PPLN waveguide chips have achieved CW gain [19, 20], yet their integration with silicon wafer-based photonic circuits has not been demonstrated."

Addition to introduction: "One way to increase nonlinearity is to use another concept for optical parametric amplification (OPA), based on exploiting the cascaded second order nonlinearity in non-centrosymmetric crystals $\chi(2)$. Optical waveguides made from periodically poled lithium niobate using mechanical dicing have enabled to operate in the continuous wave net-gain regime [20] and also demonstrated phase sensitive amplification[19]. While these works demonstrate the impressive gain that can be attained, the waveguides exhibited large cross-section due to the use of bulk dicing, and lack the scalability and flexibility of photonic integrated circuits technology. Recent advances in thin film lithium niobate integrated photonics [31] have demonstrated parametric amplifiers with gain, yet still required pulsed pulsed operation [32], and have notbeen able to attain continuous wave parametric gain, due to length restrictions, waveguide losses or photorefractive effects.

New citations:

[19] Umeki, T., Tadanaga, O., Takada, A. & Asobe, M. Phase sensitive degenerate parametric amplification using directly-bonded PPLN ridge waveguides. Optics Express 19, 6326–6332 (2011).

[20] Kishimoto, T., Inafune, K., Ogawa, Y., Sasaki, H. &Murai, H. Highly efficient phase-sensitive parametric gain in periodically poled $LiNbO_3$ ridge waveguide. Optics Letters 41, 1905–1908 (2016).

[31] Zhu, D. et al. Integrated photonics on thin-film lithium niobate. Advances in Optics and Photonics 13, 242–352 (2021).

[32] Ledezma, L. et al. Intense optical parametric amplification in dispersion-engineered nanophotonic lithium niobate waveguides. Optica 9, 303–308 (2022).

b. Performance of continuous-wave pumped fiber-based optical parametric amplifiers. The authors describe the novelty of their work from the potential to replace fiber amplifiers. To assess this, it is useful to understand current state of the art, CW fiber-based parametric amplifiers, which provide high gains. See for example the following with parametric gain ranging from 16dB to 70dB:

(vii) M. E. Marhic, N. Kagi, T.-K. Chiang, and L. G. Kazovsky, "Broadband fiber optical parametric amplifiers," Opt. Lett. 21, 573-575 (1996) – 18dB Gain

(viii) W. Imajuku, A. Takada, and Y. Yamabayashi, "Low-noise amplification under the 3 dB noise figure in high-gain phase-sensitive fibre amplifier," Electron. Lett. 35, 1954–1955 (1999) – 16 dB Gain.

(ix) J. Hansryd and P. A. Andrekson, "Broad-band continuous-wave-pumped fiber optical parametric amplifier with 49-dB gain and wavelength-conversion efficiency," in IEEE Photonics Technology Letters, vol. 13, no. 3, pp. 194-196, Mar 2001, doi: 10.1109/68.914318. – 49dB Gain.

(x) T. Torounidis, P. A. Andrekson and B. -. Olsson, "Fiber-optical parametric amplifier with 70-dB gain," in IEEE Photonics Technology Letters, vol. 18, no. 10, pp. 1194-1196, May 2006, doi: 10.1109/LPT.2006.874714. – 70dB Gain (Ref. 49)

These two bodies of work provide useful yardsticks to assess the current traveling wave parametric amplifier reported by the authors.

We thank the reviewer for the mentioned references, many of which we were already aware and cite. Indeed, these works in fibers show the immense potential of the approach. However, we respectfully remain cautious to directly compare our results 1:1 to the fiber results, which required **100s of meters of specialized and expensive optical fibers**, as well as complex SBS mitigation schemes to become possible.

To appreciate our approach, we would like to stress that in contrast, the **Si_3N_4 waveguide amplifier requires a small (5x5mm) photonic chip** and **no SBS mitigation**. Hence the Si_3N_4 waveguide amplifier overcomes core issues that have prevented widespread adoption of HLNF based OPA systems. In addition, the traveling wave parametric amplifier could be integrated with further on chip functionality: for example on-chip laser sources, soliton microcombs, or linear circuits such as AWG.

We believe a **fair comparison would be against on-chip amplifiers** (i.e., silicon wafer-based photonic integrated circuits), which we perform and discuss extensively. **To date no such OPAs in CW regime exist***[except for concurrent work *that appeared after our work had been submitted*, to be transparent and fair], and our work is **the first arXiv preprint manuscript reporting CW gain in a silicon wafer based photonic integrated circuit technology.**

While the gain in optical fiber is higher than what we achieved, ***our approach has major potential.*** Chief among the advantages is the much higher effective nonlinearity compared to fiber, and the absence of strong SBS that limits the power in optical fibers. In addition fibers and photonic integrated circuits concern two vastly different fields. We believe our OPA can be used e.g. in chip-based photonic systems to amplify light.

Also, we should emphasize that in contrast to fibers – a commercial Nobel Prize winning technology that has been optimized to its fundamental limits over decades – **the latter is not yet the case for Si_3N_4**. Indeed, taking the **recently measured fundamental absorption limit of our Si_3N_4**, this would in the future enable a gain of as much as **70 dB with less than 1 Watt of optical pump**, on a **photonic chip that is merely 20 x 20 mm (!)**. Such pump powers are realistic with hybrid integrated semiconductor sources. The cost of the photonic chip, manufactured in a scalable, low-cost high-volume fashion is more than 100x lower than the

100's of meters of highly nonlinear fiber. Therefore, our results indicate the major potential of the methods for improvements, which are realistic to expect to exceed what has been achieved in fiber.

Yet again we emphasize that achieving parametric gain in the CW regime, on a photonic chip has many more application areas: ranging from **on-chip photonic systems** for optical communications, LiDAR, low noise microwave generation, to photonic computing, etc. **Indeed the ability to endow Si3N4 with gain is of major practical importance.** Moreover, the pump lasers may also in the future be integrated with the photonic chip.

Action taken: We added additional citations on seminal works in fiber OPA to the manuscript:

[29] Marhic, M., Kagi, N., Chiang, T.-K. & Kazovsky, L. Broadband fiber optical parametric amplifiers. Optics letters 21, 573–575 (1996).

[30] Torounidis, T., Andrekson, P. A. & Olsson, B.-E. Fiber-optical parametric amplifier with 70-db gain. IEEE Photonics Technology Letters 18, 1194–1196 (2006).

The authors demonstrate 12 dB internal gain and 2 dB net gain considering all losses using a CW pump. However, the authors did not adequately contextualize their work with the aforementioned two bodies of work, especially the first.

We hope we have in our revised version explained and given sufficient credit to prior work, and also showed why the achievement of CW gain in a photonic integrated circuit, and a silicon wafer-based technology, is so promising and a key advance (given it had not been achieved before).

It may be seen from the above, that CW-pumped parametric amplifiers in waveguides on a chip have been demonstrated as early as 2009, with gains as high as 21.9dB, reported by T. Kishimoto et. al. Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017) paper W2A.12).

From this prior body of work, it might appear that the novelty in the current work is diminished. The authors should comment on this existing area of work.

As we replied earlier on pages 2 and 3 of this document, novelty of our work is not diminished since we used an very different platform. Diced PPLN waveguides show excellent and already established performance, but they cannot be integrated with other devices on chip and their length (and ultimate performance) is limited by the length of PPLN wafers. Also it is fundamentally impossible to create for example a ring resonator or waveguide splitter single chip using dicing blades. In contrast, our breakthrough is usage of PIC platform which possesses an impressive potential for the future of integrated photonics. But considering undoubtedly good results achieved on diced PPLN platform, we cite these works in revised version of our manuscript.

To replace fiber-based parametric amplifiers, the demonstration either needs to show that their work is already as good as devices used for optical communication systems, or has the potential to reach that goal. Currently, the gain achieved still falls short of fiber-optic parametric amplifiers, or even erbium-doped fiber amplifiers. This can somewhat be overcome by systems experiments showing the implementation of the amplifier. The waveguide losses demonstrated by the authors are very low and this is commendable. But can the performance of the amplifier reach the level of fiber optics when considering the loss-nonlinearity metrics in their waveguide amplifier vs. the fiber-based amplifiers?

We have performed new simulations in the supplementary information that extrapolate the performance of Si_3N_4-based dispersion engineered waveguides at the material absorption limit. In summary, we found that

Si_3N_4 based waveguide amplifiers are fundamentally able to reproduce the astonishing performance of fiber based OPA, but at a reduction in device footprint by two orders of magnitude and without the requirement for technically challenging SBS mitigation. **Hence Si_3N_4 waveguide OPA does not yet compete with fiber OPA,** but shows significant potential and provides a route towards applications that could not be addressed due to the technical difficulty of fiber-based OPA, namely because stimulated Brillouin scattering and the 100s of meters fiber length required for OPA.

As mentioned in the last point, if the fundamental absorption loss of the Si_3N_4 is reached (which corresponds to a loss of below 0.01 dB/m), substantial improvements in gains are possible of up to **70dB for merely 1 W optical input power**, due to the exponential scaling of the gain with reducing loss. This is realistic given the significant drop in loss over the past decade, and the continued improvements that are being made by many research groups around the world to reduce it further.

The currently achieved gain **(> 10 dB off chip)**, while not record, is still sufficient for some applications. As mentioned, our work is a proof of concept that Si3N4 integrated photonic circuits are now reaching a stage where significant off chip net parametric gain can be achieved. Our work established for the first time a new amplification paradigm in integrated photonics that of *continuous wave traveling wave parametric amplifiers*. For example, we could use the parametric amplifier to directly boost the output power of a soliton microcomb hosted on the same chip.

Moreover, the demonstrated gain (10 dB) could already be used to increase the SNR in optical communication or LiDAR applications, that use Si3N4 integrated photonic circuits, in future proof of concept experiments.

Concerning the **loss nonlinearity metric**, we could like to note that the effective nonlinearity of Si3N4 is ca. x100 larger than optical fiber. On the other hand, the optical losses are dB/m versus dB/km. Taken together the ratio of nonlinearity-to-loss is evidently still more favorable for optical fibers. **Yet, this is not a limitation**: two comments are in place.

First, if Si3N4 reaches the fundamental limit (0.15 dB/m), the nonlinearity to loss ratio would be equal for Si3N4 (!). This would allow achieving the best fiber amplifiers in terms of gain and required power (70 dB for only 500 mW).

Secondly, fibers could not obtain due to their very weak nonlinearity the gain that can be achieved in nonlinear integrated photonics in just a few tens of cm. Fibers OPA require significantly longer lengths and do not offer the opportunities of planar integration on a silicon chip that integrated photonics offers, to directly co-integrate the amplifier with a photonic integrated system chip. Evidently, the two platforms have very different applications in their own right. Fibers for optical communications, integrated photonics for chip-scale photonic systems (LiDAR, communication, photonic computing, microwave photonics, etc.).

Action taken: We added new calculations to extrapolate the performance of Si_3N_4-based OPA at the absorption limit and added a discussion of absorption limited performance in the SI.

Addition to Summary Section of Manuscript:

"The fundamental absorption loss [21] of stoichiometric Si_3N_4 waveguides was measured as low as 0.15 dB/m, which would facilitate parametric gain above 70 dB according to our simulations using as little as 500~mW of optical pump power, exceeding the performance of the best fiber-based parametric amplifiers [53], without the need for complex Brillouin gain mitigation systems and within 100x reduced footprints."

New Figure in Supplementary Information:

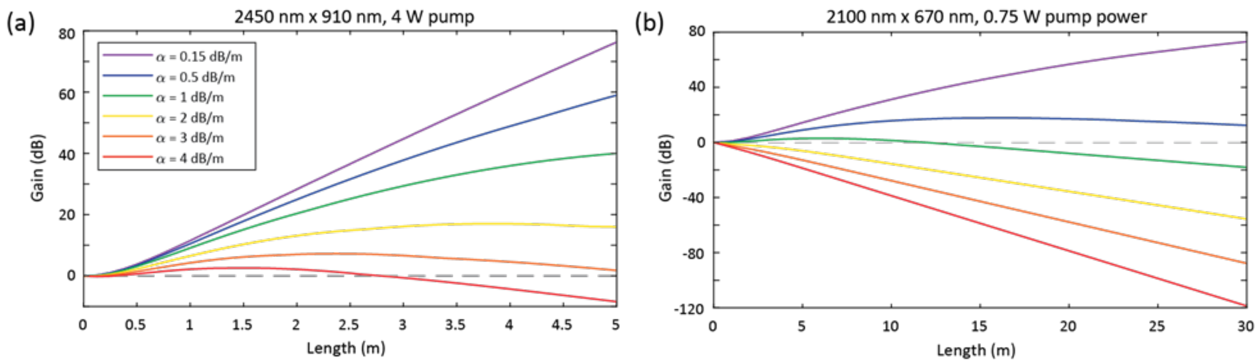

Figure 1: Numerical calculations of maximum (small) signal gain as function of waveguide loss and length.} (a) For waveguide cross-section of 2450~nm x 910~nm and pump power of 4 W, as used in the present study. The dotted and solid black lines represent the threshold for on-chip parametric gain. (b) For optimized waveguide cross section of 2100 nm x 670 nm using 0.75 W of pump power. The lowest waveguide loss value of 0.15~dB/m represents the waveguide absorption loss of Si_3N_4 structures fabricated using the photonic Damascene process at EPFL.

Addition to Supplementary Information:

"Supplementary Note 1: Numerical calculations of optical parametric gain … Herein, α denotes the linear propagation loss and γ denotes the effective nonlinearity of the silicon nitride waveguide $\gamma = \omega_P n_2/cA_{eff}$, where the n_2 is the nonlinear refractive index of the waveguide core and A_{eff} the nonlinear effective mode area.

…

The nonlinear coupled mode equations are integrated using a forward Euler scheme along the waveguide spiral of length L and signal gain and idler conversion efficiency are calculated relative to the input signal power $P_S(0)$:

…

Past the breakthrough of achieving net-gain off chip in a photonic circuit-based travelling-wave OPA, it is obvious that there exists still a large performance gap between contemporary nonlinear fiber based OPA and photonic circuit based OPA. Fiber-based OPAs are limited by fiber absorption and tight tolerance requirements to maintain close-to-zero anomalous dispersion along the fiber length. Hence it is interesting to extrapolate the potential performance of dispersion-engineered \SiN waveguides. In figure 1, we depict this extrapolation up to the limit of absorption of Si_3N_4 waveguides fabricated with the photonic Damascene process. Recent measurements via thermal response spectroscopy [1]reveal an absorption loss of stochiometric silicon nitride of 0.15~dB/m at 1550 nm with very weak contribution from Si-H and N-H bonds. Inserting this value into equations (1), we find that small signal gains in excess of 70~dB and close to the performance of fiber-based OPA [53] are realistic, if scattering loss can be reduced below the absorption limit. The results for a chip size of 5x5 mm^2, i.e. maximum waveguide length 2.5~m and a chip size of 20x20 mm^2, i.e. maximum waveguide length 30~m, are depicted in figure 1 (a) and (b), respectively.

We note that the absorption loss of 0.15 dB/m could also be improved in the future using different Si_3N_4 and SiO_2 deposition methods. Lastly, we would like to point out the recent study by Gao et al. [50] who showed that dispersion-engineered Si_3N_4 waveguides have a higher ratio of Kerr nonlinearity to absorption loss than contemporary SiO_2 and AlGaAs based waveguide systems."

It is mentioned in the discussion that based on the 0.15dB/m material loss in silicon nitride demonstrated in Ref. 19, higher gain is possible perhaps similar to that described in Ref. 49. The 0.15dB/m loss looks like it is already achievable by the group. Is there a possibility that this material can be implemented for this work to achieve even higher gain?

We appreciate the referee's comment indicating that major improvements are still possible. Indeed, we are continuing our fabrication advances, **which over the past decade have allowed us to go from 30 dB/m in 2011 to 1.4 dB/m in 2021.** Hence a nearly **x1000 fold reduction in optical losses in a decade**. These advances have been capitalized on the photonic damascene process, which has allowed to achieve integrated photonics with minimal surface roughness. We agree that the recent observation and proof of our group that the fundamental absorption limit is only 0.15 dB/m hints at the enormous potential that can still be achieved, when removing the remaining scattering sites. We have unpublished evidence that one part may be due to scattering sites in the purchased wafers. Concerning the request to add more data, unfortunately, we cannot and do not have new devices with a performance that exceeds the currently reported one. This is however subject of future work in our research group, as we believe that parametric amplifiers on chip may constitute a new area of research of ultra-low loss integrated photonic circuits. However the timescale for the improvements to take effect are too long to include in this manuscript, regrettably.

Action taken: See discussion of absorption limited performance above. We also added a sentence in the manuscript further discussing potential improvement.

The authors mainly compare their work with other demonstrations of parametric amplifiers using a pulsed pump. From this angle, it is seen from Supplementary Table 1 that the gain achieved in these prior work have much higher gain, with 50dB in Ref. 10 being achieved and higher off-chip gain of 20dB. Ref. 11 demonstrates off-chip gain of 25dB whereas work in amorphous silicon (Opt. Lett. 36, 552-554 (2011)) demonstrates off-chip gain of 6dB. The reader is left wondering if these waveguides could achieve better CW pumped parametric amplification than the silicon nitride waveguide (if for example the waveguides are lengthened and similar CW pump powers are used), considering the high gains achieved using much shorter devices. In the absence of comparable gain demonstrated in their devices, authors would need to perform an analysis of these prior work based on the loss, length, nonlinearity tradeoffs, although the best would be the demonstration of gain that is on par with some of these prior work. In addition, to replace Er-based amplifiers which can provide gain of 30dB or more, comparable gain would be needed.

We would like to respectfully make the reviewer aware that the **silicon photonic community tried unsuccessfully for more than a decade to achieve continuous-wave optical parametric gain**. This includes silicon, hydrogenated silicon, and carrier depletion structures: all these efforts could **not** produce CW gain despite the substantial progress shown along the way.

The key point is that one cannot compare CW and pulsed gain. The very reason why these works used pulsed gain is to circumvent thermal damage, free-carrier and two photon absorption, and, above all, to overcome the prohibitive waveguide propagation loss. **In fact, none of the reported platforms for integrated photonic circuits could achieve CW gain to date. We don't think CW gain in the near-infrared will be achieved in silicon waveguides due to the fundamental two-photon absorption effect.**

This fundamental problem has spurred a whole field of research into waveguide core materials with increased two photon absorption thresholds such as AlGaAs [15], ultra-silicon-rich nitride Si_7N_4 [16], GaP [34], chalcogenide waveguides [11]. We believe that many of those platforms could at some point in the future achieve the CW parametric gain breakthrough with sufficient improvements of fabrication quality and yield. The contemporary performances of these platforms are detailed in the supplementary material table 1. However, we would like to point two things: (1) out that these materials are at this time considered “exotic” in the PIC community and might need a long time to become foundry available. (2) The ultra-low loss and high-power tolerance in modern Si_3N_4 waveguides to date outperforms all those different PIC platforms.

Given then increased confinement and nonlinearity in these “third generation” waveguide materials we believe that these materials, at their respective fundamental absorption limits, might outperform Si_3N_4 in terms of optical gain bandwidth and compactness.

Concerning the comment “Although the best would be the demonstration of gain that is on par with some of these prior work” we respectfully disagree: as our goal is a photonic integrated circuit **continuous wave (CW)** optical parametric amplifier, which none of the earlier works could achieve.

Concerning the comment “The reader is left wondering if these waveguides could achieve better CW pumped parametric amplification than the silicon nitride waveguide (if for example the waveguides are lengthened and similar CW pump powers are used),” Our answer is: the waveguide losses in these works were all far higher than in our work. The high gain is purely a result of the intense pulsed optical pumping. Even if the waveguides could be lengthened (which in itself is *not* trivial as imperfections accumulate, and would be a substantial advance of the works in question) they would not show CW gain as in our case. If losses are high, gain falls down dramatically with the distance, and this also can be seen from our abovementioned simulations for absorption limited gain that we add to the supplementary materials.

Action taken: We expand the discussion of table 1 in the supplement and the implications of novel waveguide materials for the field of PIC OPA. We also add the prior works on mechanically diced PPLN.

Equations 1 and 2: Equation 2 currently incorporates only beta2 and beta4. Describe the dispersive lengths for various dispersion orders, beyond the fourth order. At what order of dispersion does the dispersive length far exceed the device length? Since the device is 2 m long in total, typically neglected orders of dispersion in integrated waveguides could become necessary to evaluate here.

This is a very important point, especially going forward to longer waveguides and low power operation, and we include this point in our discussion of the theoretical performance of an absorption limited Si_3N_4 waveguide amplifier. In all of our simulations, we include the numerically calculated propagation constant, which is simulated on a bandwidth between 100 and 400 THz. We interpolate the dispersion in this frequency range up to 12th order of dispersion. Even orders of dispersion does not contribute to the phase matching conditions.

In our present devices, β_2 is measured as -134 fs^2/mm and according to simulation, β_2 is predicted -134 fs^2/mm. Within the 1 THz amplification bandwidth, i.e. a 410 fs pulse this corresponds to a 1.2m dispersive length. The simulated β_4 is 50 fs^4/mm. The corresponding dispersive length for the 410 fs pulse is already 570m. Hence a single lobed amplification spectrum is observed and already the fourth order dispersion is irrelevant for the shape of the amplification spectrum. Generally, higher bandwidth and a double lobe is achieved (see new Figure 1b) if the 2nd order dispersion can be reduced, i.e. the dispersive length increased length as of the 4th order dispersion. It is the unique property of PIC systems that the dispersion can be controlled with high precision and great flexibility. As such, we have preliminary simulations that show that by adding a single additional layer of Si_3N_4, without the need for active alignment can compensate for the fourth order dispersion and increase the double-sided amplification bandwidth to 66 THz.

Action taken: We state the simulated second and fourth order dispersion of the measured and simulated designs. We add information on the dispersion simulations.

Addition to Supplementary Information: "Numerical simulations of waveguide dispersion are carried out in COMSOL in a range between 100 THz and 400 THz and interpolated taking into account up to 12th order of dispersion."

Addition to Main Text: Figure 1(b) depicts the simulated amplification bandwidth for our waveguide design with cross-section of 910 nm height and 2450 nm width (β_2 = -124 fs^{2}mm^{-1}, β_4 = 50 fs^{2}mm^{-1}), which supports amplification bandwidth of 1 THz. Optimizing the cross-section to for low second order dispersion at 2100 x 670 nm^2 (β_2 = -5 fs^{2}mm^{-1}, β_4 = 1800 fs^{4}mm^{-1}), amplification bandwidth exceeding 10~THz will become possible. Such a system could exceed the EDFA's C-band amplification bandwidth (black bar in Fig. 1b)) by more than three times and can be fabricated on a chip size of 5x5~mm.

The authors state, "Therefore, we achieve for the first time a net parametric gain of up to 2 dB on a photonic chip accounting for both the on-chip optical propagation loss and the fiber-chip-fiber coupling losses." – This statement is not true, because net parametric gain accounting for both coupling losses and on-chip propagation losses have also been achieved in Refs. 12, 16 and 17. In addition, Refs. (iii), (v) and (vi) in my earlier comment have also achieved net parametric gain exceeding 2dB using a continuous wave pump.

We agree that, given prior work in *mechanically diced PPLN*, we should abstain from this general broad claim. ***Hence, we changed the title and text of the manuscript to refer to our system as photonic integrated circuit.*** We however emphasize that the demonstration of a photonic integrated traveling wave parametric amplifier is in itself new and completes a decades long quest to demonstrate such devices. The last breakthrough in this field was in 2006, when Mark A. Foster and Alex Gaeta showed that broadband gain in PIC silicon waveguides was possible albeit, a low duty cycle pump was required to mitigate the two photon and free carrier absorption effects as well as thermal damage. Surprisingly, the challenge to make PIC OPA work at ***continuous wave,*** which is pivotal for most all practical applications of the technology, was not overcome in the past 15 years up to now.

As mentioned before, we appreciate the ingenuity and achievements of the PPLN micro-waveguide work however we would insist on the distinction between mechanically diced waveguide and lithographically etched waveguide technologies, as the latter can and does today support also the manufacture of general purpose and complex photonic integrated circuits, while the former has to rely on micro optical lenses for system integration.

Action taken: We changed the title of the manuscript from "Photonic chip-based…" to "Photonic integrated circuit based...", to clarify the usage of PIC platform.

Figure 3 (a). This plot shows the spectrum of (i) the pump only, (ii) the pump + signal. The authors should also show the spectrum of the signal only, so that the increased amplitude in the signal level with the pump on can be observed. Typically when there is parametric gain, the amplitude of the signal will be shown to increase compared to when the pump is off. There are no measurements which show this. I understand that there is a figure showing the modulation of the signal measured using an oscilloscope, but those are in electrical units (photodetector), and a reader would not be able to derive the quantitative gain achieved from those measurements

We would like to kindly point out that figure 2 (b) already depicts the amplification of signal at different pump powers over the whole amplification bandwidth. We have also added the requested plots as an inset to figure 3 (a), where we depict the signal and idler spectra at the minimum and maximum pump powers. We also note that the power amplification gain can be directly read from the oscilloscope trace of the photodetector. The instantaneous nature of parametric gain makes it possible to see the on-off gain directly in the time domain on linear scale. We added the signal off curve (red), to show the pump bleed and parametric fluorescence through the employed filter, which is subtracted for gain calculation. All data and plots will be made available through ZENODO upon publication of the manuscript as is standard practice in our research group.

Action taken: We added an insert to figure 3 (a) showing the signal and idler gain and frequency conversion for the minimum and maximum gain points.

The figure in Supplementary Information (S2) which was measured using the maximum hold mode on the spectrum analyzer. In these, individual example spectra of the signal comparing pump on and off was also not shown. The authors should show a few of these example spectra, perhaps at the wavelength extremes within the range measured (eg. 1545nm and 1565nm), at the peak gain wavelength and a couple more wavelengths within the range. In addition, figure S2, being a measurement, should show the individual data points in the curve plotted, as opposed to just a line plot. How does the simulation result compare with the experimental result in figure S2? Is there any reason why the range outside of 1545nm and 1565nm was not characterized?

First, the range outside 1545 to 1565 nm was not depicted due to the absence of parametric fluorescence or gain, caused by the large second order dispersion of the employed device. The plots depicted in figure S2 have 10 Million points each, afforded by the extremely high resolution of the frequency comb calibrated scanning diode laser spectrometer, which we rebuilt into an OFDR. Hence, no marker style plots can be depicted. The comparison between simulation and experiment for the dispersion measurement is quite good, the former yielding a dispersion of -124 fs^2/mm and the latter yielding -135 fs^2/mm. We use material dispersion information obtained by ultra-wideband spectral ellipsometry and fitted with a 3-term Sellmeier model comparable to Luke et al., Opt. Lett. 40, 4823-4826 (2015).

Action taken: We changed the line plots in Figure 2(b,d) and SM Figure 3 to marker point plots.

Figure 3 (a) measures the gain as a function of input power. At higher powers, the discrepancy with calculations increases. The authors should address this. What effects could be causing this deviation?

We thank the reviewer for pointing out this issue. The short answer is that the precise reason for this deviation is unknown. Recent measurements by the Vahala group on our samples reveal that the Kerr effect is about 10% smaller than initially measured by Ikeda et al. Opt. Express 16, 12987-12994 (2008). This is likely due to the higher quality of the material used in modern Si_3N_4 waveguides with ultra-long absorption loss. Victor Torres Company from UChalmers recently reported at OFC that they observe also a 3dB discrepancy between simulation and measurement in Si_3N_4 based CW OPA. They attribute the discrepancy to a reversible effect, where the absorption loss of the subtractive waveguide increases with high power, which again subsides in a few days. While we have not recognized any change in the transmission from low to high power in our samples, we don't rule out that the same effect also occurs in our photonic Damascene waveguide, which we are investigating actively. Another effect that might reduce the effectiveness of waveguide OPA is the fact that some of the pump power might be scattered to and from the higher order waveguide modes, hence reducing the effective pump power.

Action taken: We added a sentence on the possible issues or waveguide OPA into the main manuscript.

Addition to main manuscript: The results are in agreement with numerical calculations of the gain up to a peak input power of 5 W where we see a deviation up to 2.5 dB, which might be related to was recently attributed to a temporary increase of Si_3N_4 propagation loss after high power operation [50]. However, we do not observe a reduction in the pump transmission at any of the used optical power levels.

New citation: [50] Torres-Company, V., Ye, Z., Zhao, P., Karlsson, M. & Andrekson, P. A. Ultralow-loss silicon nitride waveguides for parametric amplification. In 2022 Optical Fiber Communications Conference and Exhibition (OFC), 1–3 (IEEE, 2022).

The main claim of the paper is continuous-wave pumping as opposed to pulsed pumping in other schemes. This is a good achievement. However, a more robust discussion on the tradeoffs between the different platforms is lacking. Supplementary table 1 shows different parameters and gain achieved. Gs is considerably higher in Refs. 6, 8, 10 and 14, The comparison with prior work on continuous-wave pumped optical parametric amplifiers (Refs above with gain as high as 21.9dB) is important to compare but not included.

As we discussed earlier, we extend this table to cover other platforms.

Action taken: Add the work by T. Kishimoto et al. to the SI table 1.

Overall, I find the work from the authors interesting, but without sufficient contextualization with existing work. Considering the higher gains achieved in other demonstrations of CW pumped on-chip waveguide parametric amplifiers (21.9dB in Ref. (vi)), much higher gains in fiber optic parametric amplifiers (70dB in Ref. 49), and significantly higher gains in pulsed pumped waveguide amplifiers (50W in Ref. 10), a much more rigorous discussion and experiments which show better amplification performance in the traveling-wave silicon nitride waveguide amplifier are warranted.

We hope that our reply clarified that we have achieved **for the first time a CW parametric amplifier in a photonic integrated silicon wafer-based platform:** a goal that has been **elusive for more than 15 years.** We, therefore, hope that the reviewer understands that we cannot provide more data than the gain we have reported. We also hope to have clarified the major difference between CW amplifier and pumped amplifier which is not academic: it enables amplification of arbitrary waveforms and continuous data streams and importantly it also allows in the future a route to the on-chip integration of the pump lasers – which to date have been successfully integrated into the silicon photonics platform. We have followed the request and now put our work into the context of prior work, highlighting the **pioneering efforts in both PPLN and Fibers more clearly**. We hope that we have clarified and now provide the rigorous discussion and comparison that the referee required.

Referee #2 (Remarks to the Author):

Since the editors asked me for a quick review due to another reviewer dropping out, I'm going to be brief:

I can say that it's (a) an extremely important, milestone result, and (b) very well-written, clear, and of high quality. I'd endorse publishing it as-is in Nature. It's one of the best papers I've read recently in integrated optics.

I'm not going to transmit any of the traditional trivial quibbles. Go forth and publish this!

We sincerely thank the reviewer for his/her acknowledgment and strong endorsement of our work.

Referee #3 (Remarks to the Author):

Dear Authors,

I'm happy for having had the possibility to review your paper**.** The reported results, in terms of low losses, parametric gain and device bandwidth are surely novel and relevant. The data are generally well presented, and the rationale is clear.

We thank the reviewer for his/her commitment to review our work and the appreciation of our work.

My main doubt with the present submission is that the general claims are a bit exaggerated with respect to the real novelty and improvement reported in the text. The results are surely interesting, but they are mainly technological optimization and not real breakthrough ideas.

Yes, we agree. Many advances today rely on technological optimizations; the development of optical fibers – truly revolutionary and Nobel Prize winning – has been a steady optimization over a time span of 15 years. There are numerous examples that show that indeed technological steps and scientific breakthroughs leapfrog. Many scientific advances would not take place without the corresponding technological advances. The current results demonstrate what was not possible over the past 15 years since Mark Foster and Alexander Gaeta reported pulsed gain in silicon.

On the same token there are many breakthrough ideas that unfortunately never lead to actual technological applications. For instance: photonic computing in the 1980' was a conceptual breakthrough - but ultimately did not lead to any new technologies. There are many other examples – and e.g., contemporary topological photonics – significantly featured in numerous journals – may not lead to any technological developments.

We firmly believe that our work marks what will likely be only the first example of a viable photonic integrated parametric amplifier operating in the CW regime, capable of amplifying weak signals, with quantum limited noise performance with lithographically defined gain, i.e., dispersion engineering. The achievement of CW marks a key technological threshold that will inspire other researchers to seriously pursue further work. We believe that Nature editors should decide to what extend also technological breakthroughs should be exposed to the readership. We ourselves are convinced that this should be the case, in cases where significant future development could result.

I do not foresee a potential impact as wide as I would expect from a Nature article; for this reason I consider the paper more suitable for "Light: science & applications", than for "Nature".

We respectfully disagree on the potential impact. We perceive that the achievement of CW parametric gain on chip, tried for 15 years, has major potential.

- The ability to endow PIC with gain has important repercussions as amplification of signals is key to virtually all applications of integrated photonic circuits. The ability to in the future also integrated the laser to pump the amplifier on chip, makes this a compelling technology.
- The amplifier technology is very flexible, as the gain is optically tunable (in contrast to III-V based amplifiers that need to be adapted to the input power level).
- The amplification is inherently unidirectional (which is a key asset given that reflections from chip facets can cause other semiconductor amplifiers to start lasing, limiting gain).
- Combined with other devices such parametric amplifiers could be used to amplify signals in applications ranging from LiDAR, coherent telecommunications, integrated lasers – as virtually all applications require amplification.

We are sure that our work will inspire and trigger future developments in other platforms such as GaP on insulator, AlGAs on insulator, SiC on insulator, lithium niobate on insulator and other platforms that feature strong optical nonlinearities.

Regarding the technical comments, I believe that the following points should in any case be addressed before publication in a journal:

• 1) It seems to me that one of the main improvements allowing the realization of such a component is the realization of a super low loss Silicon Nitride. It would be important to highlight which are the key steps in order to obtain so low losses.

We are happy to read the appreciation for countless hours spent in the cleanroom and dedicated to improving waveguide propagation loss over the past ten years. Because we just recently published an extensive report on the updated photonic Damascene process [21], we refrained from including a large number of details in this report that focusses solely on the achievement of CW OPA in photonic circuits. We realize here that we did not mention the methods section in the main text. In this methods section we already mention the importance of DUV stepper lithography but add a more in-depth reasoning behind the chosen fabrication methods.

Action taken: We add a sentence to the main text highlighting the methods section, which we also expand with additional context and qualification.

Addition to main text:

"Fabrication details are provided in the methods section."

Additions to the methods section:

"Thermal reflow of the Damascene preform reduces scattering loss between 30 % and 50 % [21].

…

The triple annealing strategy, i.e. substrate reflow, Si_3N_4 anneal, and SiO_2 top cladding anneal, facilitated by the photonic Damascene process, is key to the achievement of ultra-low waveguide scattering and absorption loss.

…

Light is coupled into the waveguide facets as etched."

• 2) In the conclusion you cite a material loss of 0.15 dB/m, which is much lower than the waveguide loss of 2.5dB/m. Although it is clear, to those working in the field, that it is already an extremely good value, it would be important to explain in the text which are the factors causing such an increase of the linear loss parameter.

We believe that our waveguides are currently limited by scattering loss. Ongoing investigations are looking into the question whether scattering centers occur in the bulk or at the waveguide sidewall interface. We have unpublished evidence that one part may be due to scattering sites in the purchased wafers but cannot substantiate a solid discussion of these effects at this time.

• 3) I was quite surprised, while reading your paper, by the "relatively high" coupling losses of your chip, which are evaluated as 2.5 dB/cm. Generally systems using lensed fibers and inverse tapers can achieve insertion losses lower than 1 dB/facet. Can you please explain why you had so high losses?

Two key advancements that were instrumental in reducing the waveguide spiral loss are: 1) Using DUV stepper lithography to avoid stitching errors and improve uniformity, but at the cost of minimal feature size, which is less than 100 nm for Ebeam and 250 nm for our DUV machine (248 nm). 2) Using thicker nitride films for reduced overlap with waveguide sidewalls, which also reduces the effectiveness of inverse tapers due to the increased minimal core cross-section. Recently workarounds based on a second and thinner layer of Si_3N_4 have been proposed and implemented in the visible wavelength range and are actively pursued in by commercial foundries. Similar concepts can be used in the infrared domain to achieve coupling losses to SMF28 of less than 1 dB per facet even for high confinement devices.

Lin, Yiding, et al. "Low-loss broadband bi-layer edge couplers for visible light." Optics Express 29.21 (2021): 34565-34576.

• 4) Please clearly specify in the figure captions if the reported power levels (especially for the pump) are in the fiber or in the chip. It would be nice, to understand also the reproducibility of the system, what is the power of pump beam immediately after the EDFA.

We clarify that all powers given in figures 2 and 3 are in regard to the power at the lensed fiber tip. The nominal maximum power of the amplifier is 15 W. Most loss is incurred in the tunable bandpass filter which we use for ASE rejection.

Action taken: Add model numbers for amplifiers lasers and filters to the supplementary materials section.

Addition to Supplementary Information: "The pump laser is amplified using a high-power EDFA (Keopsys CEFA-C-PB-HP-43, maximum power 15~W). We filter the amplified spontaneous emission light (ASE) using a tunable thin-film bandpass filter (FOTF-025224323, insertion loss 2 dB) after the amplified pump light passes a high-power polarization maintaining isolator (Advanced Fiber Resources HPMI-55-20-2-L-1-F-P)."

• 5) It would be extremely helpful to show the supplementary table 1 directly in the main text, and to add some real FOM, e.g. giving the G_S or G_I divided by the square of the pump power, as the FWM process efficiency is quadratic on pump level. Please also add (eventually in the supplementary material) all the equations used as definition of the different FOM.

We thank the reviewer for suggesting the addition of a material independent FOM to greatly simplify the trade-offs between different material systems. Given the great length of the table and the additions that we have done regarding the comments by reviewer #1, we do not add the table to the main text which is more suited to a review style paper.

Action taken: We add a sentence to the main text highlighting the methods section, which we also expand with additional context and qualification. We also added another column to the table implementing the proposed figure of merit.

Addition to Supplementary materials:

"The nonlinear figure of merit of Si_3N_4-based waveguide OPA has increased 100-fold over the last decade."

• 6) As a reference, although for several reasons they are not very suitable for these applications, it would be nice also to see the comparison with results based on PPLN waveguides.

We admit that we overlooked the works on mechanically diced PPLN waveguides in the field of OPA and phase sensitive amplification. We do not believe that the results achieved in the PPLN platform does impact the novelty of our results of achieving net gain in a photonic integrated circuit platform. We refer to our extended discussion in response to a similar question of reviewer #1 (pages 2-3 of this document) and our changes made to the manuscript title abstract and introduction that we implemented.

Action taken: To better clarify the novelty, we have also adapted our title. From “Photonic chip-based…” to “Photonic integrated circuit based...”, to emphasize the PIC platform. We also added discussion of mechanically diced PPLN waveguide technology in Abstract and Introduction.

• 7) How high should the pump power be to achieve at least transparency (i.e. on-chip gain=10dB) in case of a 1mW and a 10 mW signal?

According to our simulations, signal strengths up to 10 dBm fall well within the small signal regime. We find that the 1 dB gain compression occurs for signal input power is at 250 mW. Hence the power required on the input lensed fiber for transparency is around 7 W in both cases. The corresponding power in the beginning of the waveguide is 4 W.

Action taken: We mention the simulated gain compression point in the main manuscript.

Addition to the main manuscript: “Our simulations indicate that the 1 dB gain compression point of the photonic circuit based OPA is as high as 250 mW”

• 8) Can you please comment on the possibilities to reduce the pump-power requirements? As far as I know, a system with more of 10W of CW pump being delivered to the chip is probably not going to be considered as very appealing for real world applications.

We totally agree that 10 W of continuous wave power is too much and must be reduced for real world applications. We hence performed numerical simulations that outline the potential performance of Si_3N_4-waveguide based OPA and added a new section to the SI. For a detailed discussion of this point, we refer to our answer to reviewer #1 on page 5 - 7 of this document.

Action taken: We added new calculations to extrapolate the performance of Si_3N_4-based OPA at the absorption limit and added a discussion of absorption limited performance in the SI.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

I have read through the detailed response from the authors. I am happy to say that the manuscript is much improved with the additions and new discussions. Specifically, the posturing of the paper to now address photonic integrated circuit rather than chip is very appropriate. The discussion around fiber amplifiers and in particular $LiNbO_3$ chip-based amplifiers is an important addition, the latter of which is especially salient given their long history in the field and good on-chip performance though as articulated by the authors, come with their own set of challenges for integrated circuits. The added details for the simulations are good. The authors make a convincing case for the direction that optical parametric amplifiers need to move towards.

I recommend publishing the paper with some minor comments as follow:

(1) This discussion put forth by the authors in the appended paragraph below is very interesting especially for the photonic integrated circuit community. I recommend including this in the manuscript, perhaps close to Supplementary Table 1. This whole discussion is a balanced and thoughtful argument as to why the currently reported silicon nitride amplifier is well placed in the field.

"Silicon photonic community tried unsuccessfully for more than a decade to achieve continuous-wave optical parametric gain. This includes silicon, hydrogenated silicon, and carrier depletion structures: all these efforts could not produce CW gain despite the substantial progress shown along the way.
The key point is that one cannot compare CW and pulsed gain. The very reason why these works used pulsed gain is to circumvent thermal damage, free-carrier and two photon absorption, and, above all, to overcome the prohibitive waveguide propagation loss. In fact, none of the reported platforms for integrated photonic circuits could achieve CW gain to date. We don't think CW gain in the near-infrared will be achieved in silicon waveguides due to the fundamental two-photon absorption effect.
This fundamental problem has spurred a whole field of research into waveguide core materials with increased two photon absorption thresholds such as AlGaAs [15], ultra-silicon-rich nitride Si_7N_4 [16], GaP [34], chalcogenide waveguides [11]. We believe that many of those platforms could at some point in the future achieve the CW parametric gain breakthrough with sufficient improvements of fabrication quality and yield. The contemporary performances of these platforms are detailed in the supplementary material table 1. However, we would like to point two things: (1) out that these materials are at this time considered "exotic" in the PIC community and might need a long time to become foundry available. (2) The ultra-low loss and high-power tolerance in modern Si_3N_4 waveguides to date outperforms all those different PIC platforms. Given then increased confinement and nonlinearity in these "third generation" waveguide materials we believe that these materials, at their respective fundamental absorption limits, might outperform Si_3N_4 in terms of optical gain

bandwidth and compactness."

(2) Note a typo in the paragraph above: Si7N4 should be corrected to Si7N3.

(3) Line 131 in Supplementary Information has an incomplete sentence: "The material independent figure of m" appears to be missing some text.

(4) An optional suggestion: The authors could consider changing the FOM to fully linear quantities or fully logarithmic quantities. Currently it is the Gain in dB divided by the square of the pump power in Watts. For consistency, I suggest changing this FOM to Gain (linear units)/Pump Power2 (Watts) OR Gain (dB)/Pump Power2 (dBm).

Referee #3 (Remarks to the Author):

To authors and editors:

As I said in my prior review, this is an extremely important result. Having read the very careful and thoughtful reviews by reviewers 1, 2 and 4, I am even more confident that this result is going to be high-impact across multiple fields of optics. I'll be shocked if this paper doesn't end up with thousands of citations - it's the beginning of a new field.

Getting practical all-optical gain in a silicon-compatible optical platform has been an ongoing effort for longer than I've been in the field - that is to say more than 25 years. A lot of things have been tried. Sputtering glass. Implantation into silicon. Bonding new materials on top. Polymer nonlinearities. Plasmons to get high confinement. Slot waveguides. None of them produced an amplifier that was worth using for any real application, or that provided the potential to replace multi-meter scale erbium doped fiber amplifiers, or kilometer-scale raman amplifiers.

The only thing that's been done that's had any commercial impact has been bonding III/V gain chips onto silicon. That's useful, but it does NOT provide an ultrafast nonlinearity - it just provides gain.

This result offers a path toward building amplifiers that are compact, inexpensive, wafer scale, and that will have better performance (in the limits) than today's fiber amplifiers. It's hard to overstate the potential impact of this result in the datacom and telecom world - a better, more compact amplifier could find applications from subsea all the way to datacenter applications. There are lots of places where space is in fact the biggest constraint. And the combination of being able to build many of these on a chip with improved noise figures could have an even greater impact.

It also opens the possibility of building fundamentally new kinds of systems on chip, since compact elements with high ultrafast nonlinearity will then be able to be built at scale and coupled together. This could enable a whole generation of new systems-on-chip.

The first reviewer made good points about narrowing the rhetoric a bit to emphasize the integrated photonics part of this result - lithium niobate and fibers are indeed the incumbent systems, and the positioning of the result is better emphasizing the integrated photonics and silicon photonics part of things. This does not diminish the impact; the fastest growing area of photonics in the commercial world for the past decade has been silicon and silicon-compatible platforms.

As for the third reviewer's points about impact, I respectfully disagree. I can see a dozen commercial applications for this result more or less immediately, and especially after some engineering to push losses down and performance up. Given that this is the first proof-of-concept result in the platform, such improvements are to be expected.

Speaking as someone with a lot of industry experience, I can just assert that this will be of huge interest from a commercial perspective. This is very likely to be a hugely impactful result.

Their comments about 2.5dB insertion losses at the edge couplers being relatively high seem to reveal that they're looking at things from a purely academic viewpoint - getting to sub-1dB numbers requires either the choice of a waveguide design that optimizes the couplers, or a considerable effort. Expecting much lower coupling losses for this kind of academic result is not reasonable, and has nothing to do with the novelty of the results here.

I believe that all of the comments from the first and third reviewers have been comprehensively integrated, and the responses are really quite compelling. I'd strongly urge the editors to publish this result.

Referee #3 (Remarks to the Author):

Thanks for answering to all the technical comments and questions

Author Rebuttals to First Revision:

Resubmission of our manuscript "Photonic integrated circuit based continuous-travelling-wave parametric amplifier"

Here we present a detailed answer to the review. Our replies are highlighted in blue, while the red text sections indicate additions to the manuscript.

Referee #1 (Remarks to the Author):

I have read through the detailed response from the authors. I am happy to say that the manuscript is much improved with the additions and new discussions. Specifically, the posturing of the paper to now address photonic integrated circuit rather than chip is very appropriate. The discussion around fiber amplifiers and in particular LiNbO3 chip-based amplifiers is an important addition, the latter of which is especially salient given their long history in the field and good on-chip performance though as articulated by the authors, come with their own set of challenges for integrated circuits. The added details for the simulations are good. The authors make a convincing case for the direction that optical parametric amplifiers need to move towards.

We thank the referee for the effort to review our revised manuscript and for pointing out the important work on lithium niobate based TWOPA systems in his first review. We are delighted to the positive recommendation of the referee and the appreciation of our work and the added discussions of prior art in the revised manuscript.

I recommend publishing the paper with some minor comments as follow:

(1) This discussion put forth by the authors in the appended paragraph below is very interesting especially for the photonic integrated circuit community. I recommend including this in the manuscript, perhaps close to Supplementary Table 1. This whole discussion is a balanced and thoughtful argument as to why the currently reported silicon nitride amplifier is well placed in the field.

"Silicon photonic community tried unsuccessfully for more than a decade to achieve continuous-wave optical parametric gain. This includes silicon, hydrogenated silicon, and carrier depletion structures: all these efforts could not produce CW gain despite the substantial progress shown along the way.

The key point is that one cannot compare CW and pulsed gain. The very reason why these works used pulsed gain is to circumvent thermal damage, free-carrier and two photon absorption, and, above all, to overcome the prohibitive waveguide propagation loss. In fact, none of the reported platforms for integrated photonic circuits could achieve CW gain to date. We don't think CW gain in the near-infrared will be achieved in silicon waveguides due to the fundamental two-photon absorption effect.

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We thank the referee for pointing out points to improve the manuscript. We decided to add a few of the raised points into the methods section. We reorder the extended data table 1 to reflect the distinction given in the argument between silicon, silicon nitride and "third generation waveguide materials"

Action taken: Expanded supplementary note: "Comparison of state-of-the-art TWOPAs using integrated photonics" and added the note to the methods section and reordered the extended data table 1.

(2) Note a typo in the paragraph above: Si7N4 should be corrected to Si7N3.

We thank the referee for the careful study of the manuscript and revised the mistake.

(3) Line 131 in Supplementary Information has an incomplete sentence: "The material independent figure of m" appears to be missing some text.

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(4) An optional suggestion: The authors could consider changing the FOM to fully linear quantities or fully logarithmic quantities. Currently it is the Gain in dB divided by the square of the pump power in Watts. For consistency, I suggest changing this FOM to Gain (linear units)/Pump Power2 (Watts) OR Gain (dB)/Pump Power2 (dBm).

We disagree with the referee because, we believe that the formulated figure of merit reflects the fact that the phase matched Kerr parametric gain depends exponentially on the input power. Hence in the proposed state it directly reflects the ability to generate net gain in a specific structure with limited input power. Indeed, the best values are found for silicon and AlGaAs waveguides. The achievable performance in those waveguides is limited by two-/three- photon absorption and thermal damage, not their linear loss.

Action taken: We revise the figure of merit of the OPA devices as G_S/P_{pk}, instead of G_S/P_{pk}^2 to properly reflect the dependence of gain on the input power in the extended data table 1 .

Referee #3 (Remarks to the Author):

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I believe that all of the comments from the first and third reviewers have been comprehensively integrated, and the responses are really quite compelling. I'd strongly urge the editors to publish this result.

We thank the referee for the careful study of the revised manuscript and the very strong endorsement of our work.

Referee #3 (Remarks to the Author):

Thanks for answering to all the technical comments and questions.

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