A photonic integrated continuous-travelling-wave parametric amplifier

The ability to amplify optical signals is of pivotal importance across science and technology typically using rare-earth-doped fibres or gain media based on III–V semiconductors. A different physical process to amplify optical signals is to use the Kerr nonlinearity of optical fibres through parametric interactions. Pioneering work demonstrated continuous-wave net-gain travelling-wave parametric amplification in fibres, enabling, for example, phase-sensitive (that is, noiseless) amplification, link span increase, signal regeneration and nonlinear phase noise mitigation. Despite great progress, all photonic integrated circuit-based demonstrations of net parametric gain have necessitated pulsed lasers, limiting their practical use. Until now, only bulk micromachined periodically poled lithium niobate (PPLN) waveguide chips have achieved continuous-wave gain, yet their integration with silicon-wafer-based photonic circuits has not been shown. Here we demonstrate a photonic-integrated-circuit-based travelling-wave optical parametric amplifier with net signal gain in the continuous-wave regime. Using ultralow-loss, dispersion-engineered, metre-long, Si₃N₄ photonic integrated circuits on a silicon chip of dimensions 5 × 5 mm², we achieve a continuous parametric gain of 12 dB that exceeds both the on-chip optical propagation loss and fibre–chip–fibre coupling losses in the telecommunication C band. Our work demonstrates the potential of photonic-integrated-circuit-based parametric amplifiers that have lithographically controlled gain spectrum, compact footprint, resilience to optical feedback and quantum-limited performance, and can operate in the wavelength ranges from visible to mid-infrared and outside conventional rare-earth amplification bands.

The ability to amplify optical signals is of paramount importance across science and technology. Although optical fibres have been an instrumental development for optical communications, the choice of wavelength of 1,550 nm (the C band and L band) followed the development of erbium-doped fibre amplifiers (EDFAs). The invention of EDFAs has revolutionized optical communications by replacing electrical signal regeneration and enabling optical signals to propagate over more than 12,000 km (ref. 21). This led to a strong increase in communication bandwidth at low cost, which was critical to the development of the World Wide Web as we know it today. Optical amplification can also be achieved using the third-order \( \chi^{(3)} \) (that is, Kerr) nonlinearity of fibres and waveguides by means of the parametric process. Such parametric amplifiers have been originally developed in the microwave domain, in which the term ‘parametric’ designates the variation of system parameters, such as the capacitance of a transmission line or the refractive indices of optical materials. The large nonlinearity of Josephson junctions has led to the development of compact, chip-based travelling-wave parametric amplifiers (TWPAs) in the microwave domain that are quantum-limited, exhibit broadband gain and enable single-shot superconducting qubit readout and measurements of quantum jumps, relevant to quantum information processing.

Parametric amplifiers have several unique properties that distinguish them from amplifiers based on optical transitions. Parametric amplifiers can achieve gain in virtually any wavelength window. The gain can be broadband and is determined uniquely by the waveguide dispersion, leading to gain by waveguide design. This makes parametric amplifiers attractive candidates to achieve gain in wavelength ranges that are not covered by conventional gain media. Parametric amplifiers operate close to the fundamental quantum noise limit of 3 dB for a single tone and can also be operated in the phase-sensitive configuration, allowing noiseless amplification. Furthermore, they can have variable gain and are inherently non-reciprocal, that is, the amplification is unidirectional, which strongly increases their resilience to optical feedback from chip facets and fibre splices. These properties have made parametric amplifiers pivotal for signal regeneration and wavelength conversion, and the most promising candidates to extend optical communication systems to new wavelength ranges. Yet, despite these promises and pioneering achievements of net continuous and broadband gain in fibre-based TWPAs, the use
of such parametric amplifiers has been severely limited today by the low Kerr effective nonlinearity and fabrication tolerances of optical fibres. One way to increase nonlinearity is to use another concept for optical parametric amplification, based on exploiting the cascaded second-order nonlinearity in non-centrosymmetric $\chi^2$ crystals. Optical waveguides made from PPLN using mechanical dicing have allowed operating in the continuous wave net-gain regime\textsuperscript{27} and also demonstrated phase-sensitive amplification\textsuperscript{28}. Although these works demonstrate the impressive gain that can be attained, the waveguides exhibited large cross section owing 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 photonic\textsuperscript{29} have demonstrated parametric amplifiers with gain, yet still required pulsed operation\textsuperscript{30} and have not been able to attain continuous-wave parametric gain, owing to length restrictions, waveguide losses or photorefractive effects. By contrast, the pioneering work of ref.\textsuperscript{3} demonstrated, using strongly pumped optical fibres, the regime of continuous-wave net-gain travelling-wave parametric amplification, which is quantum-limited, exhibit broadband and strong gain, and has also been used for phase-sensitive (noiseless) amplification\textsuperscript{4}.

Over the last decade, there has been notable progress in new nonlinear photonic integrated platforms, including Si$_3$N$_4$ (refs.\textsuperscript{18,31,32}), AlGaAs (ref.\textsuperscript{33}), GAP (ref.\textsuperscript{34}), tantala\textsuperscript{35} and chalcogenide\textsuperscript{36}. These integrated platforms exhibit much higher effective third-order nonlinearity than that of silica fibres and allow lithographically tailored dispersion. Demonstrating a TWPA based on integrated photonic circuits, in particular those already available through commercial wafer-scale foundry, would provide a new amplification principle to integrated photonics and enable integration with existing devices and components. Yet, a photonic-integrated-circuit-based continuous-wave TWPA in the optical domain (that is, a TWOPA), using the third-order nonlinearity and capable of amplifying arbitrary temporal input signals has, so far, not been demonstrated. Net gain has only been achieved using pulsed optical pump fields to overcome the large optical losses of waveguides, limiting the practical use as a general-purpose amplifier, capable of amplifying arbitrary temporal input signals.

Here we overcome this challenge and demonstrate a photonic-integrated-circuit-based TWOPA that operates in the continuous-wave regime and achieves net gain, even in the presence of fibre-to-chip coupling loss. Our work is based on recent advances of ultralow-loss, dispersion-engineered, nonlinear, Si$_3$N$_4$ integrated waveguides that are fabricated using the photonic Damascene reflow process\textsuperscript{37}. Fabrication details are provided in Methods. Stoichiometric Si$_3$N$_4$ exhibits a transparency window from the visible to mid-infrared and a bandgap of $3\text{ eV}$ that prohibits two-photon absorption in the 1,550 nm band. It can be deposited by means of chemical vapour deposition and is compatible with complementary metal–oxide–semiconductors (also known as CMOS)\textsuperscript{38}. By contrast, Foster et al.\textsuperscript{3}, in their pioneering work, have achieved 4.2 dB on/off transient gain in a silicon-on-insulator waveguide, despite the two-photon absorption of silicon in the telecommunication bands, by using a picosecond pulsed laser for amplification to achieve high pump peak power. Most state-of-the-art works in Kerr-based\textsuperscript{39,40,13-15} parametric amplification follow a similar scheme using pulsed pump lasers rather than continuous-wave lasers. Numerous previous studies have reported on the progress of photonic-integrated-circuit-based TWOPAs and investigated new materials such as hydrogenated amorphous silicon (a-Si:H)\textsuperscript{41}, AlGaAs (ref.\textsuperscript{42}) and silicon-rich nitride (Si$_7$N$_3$)\textsuperscript{43}. The performance of silicon-on-insulator waveguide systems has also been improved by operation in the mid-infrared region\textsuperscript{44} or by active extraction of generated photocarriers in a p–i–n junction\textsuperscript{45}. The main focus of these works is the improvement of the so-called nonlinear figure of merit, that is, the relation between the Kerr nonlinearity and the nonlinear absorption by careful balance of the electronic bandgaps and pump wavelengths. Yet, photonic-integrated-circuit-based TWOPAs with continuous net gain have remained out of reach, even though time-continuous and spectrum-continuous travelling-wave amplification is pivotal for successful implementation of amplifier technologies in modern optical communication systems, as well as emerging applications such as LiDAR.

Continued and substantial advances to reduce waveguide losses in integrated photonics\textsuperscript{46,47} over the last decade now enable a fundamental change and indicate that continuous net-gain TWOPAs are possible. Recent advances in fabrication\textsuperscript{46,47} have achieved crack-free Si$_3$N$_4$ photonic integrated circuits featuring tight optical confinement, high peak and average power-handling capability, low Brillouin gain\textsuperscript{48}, wideband engineering of anomalous group velocity dispersion (GVD)\textsuperscript{49} and ultralow optical losses near 1 dB m\textsuperscript{−1} with $\alpha_{\text{NL}}$ nonlinear coefficient of up to 1 W\textsuperscript{−1} m\textsuperscript{−1} and negligible nonlinear absorption at telecommunication bands. Such Si$_3$N$_4$ integrated photonic circuits are already available by means of commercial foundry and form the basis of a range of passive and active devices, including microcombs\textsuperscript{50} and single-frequency lasers. Building on these advances and realizing compact, metre-long photonic-integrated-circuit-based spiral waveguides, with uniform and engineered dispersion, one can achieve efficient parametric generation and amplification without the need for low-duty cycle pumping\textsuperscript{51} or resonant enhancement\textsuperscript{52}.

Single-pump parametric amplification can be described using a frequency-domain model of waveguide modes coupled through nonlinear degenerate four-wave mixing mediated by the optical Kerr effect\textsuperscript{53}, the general principle of which is shown in Fig. 1a,b. A signal and a strong pump are combined and coupled into an optical waveguide, in which power is transferred from the pump to the signal through degenerate four-wave mixing. For every annihilated pair of pump photons of frequency $\omega_p/2n$, a signal photon $\omega_s/2n$ is generated together with a phase-conjugated idler photon $\omega_i/2n$, that is, $2\omega_p = \omega_s + \omega_i$. In the absence of optical propagation loss, the signal power $P_s(L)$ and idler power $P_i(L)$ at the end of the waveguide of length $L$ are as follows:

$$P_s(L) = P_s(0) \left[ \frac{g P_s(0)}{g} \sinh(gL) \right]^{-2},$$

$$P_i(L) = P_s(0) \left[ \frac{g P_s(0)}{g} \sinh(gL) \right]^{-2},$$

in which $P_s(0)$ and $P_i(0)$ are the incident powers of the signal and the pump, respectively. The parametric gain coefficient is derived as $g = -\Delta \beta (\Delta \beta/4 + \gamma P_s(0))$ with the effective nonlinearity $\gamma = \frac{\alpha_{\text{NL}}}{c \text{Re} \chi^2}$, in which $\alpha_{\text{NL}}$ is the nonlinear refractive index (Kerr nonlinearity) of the waveguide core, $\text{Re} \chi^2$ the nonlinear effective mode area, $c$ the speed of light in vacuum and $\omega$ is the optical frequency. The coherent nature of parametric interaction in the waveguide demands to fulfil a stringent phase-matching condition for efficient amplification:

$$\Delta \beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p),$$

$$= \beta_s(\omega_s - \omega_p)^2 + \frac{\beta_i}{12}(\omega_s - \omega_p)^4,$$

in which $\beta$ denotes the optical propagation constant and $\beta_s$ and $\beta_i$ are the second-order and fourth-order derivatives with respect to $\omega$, respectively. The GVD parameter $\beta$ of integrated waveguides can be engineered over a wide range by variation of waveguide cross-sectional geometry\textsuperscript{54,55}. As such, both fibre-based and waveguide-based TWOPA systems can provide amplification bandwidths that greatly exceed those of rare-earth-doped fibre amplifiers. Figure 1b depicts the simulated amplification bandwidth for our waveguide design with cross-section dimensions of 910 nm height and 2,450 nm width ($\beta_s = -124 \text{ fs}^2 \text{ mm}^{-1}$, $\beta_i = 50 \text{ fs}^4 \text{ mm}^{-4}$), which supports an amplification bandwidth of 1 THz. By optimizing the cross section for low second-order dispersion at 2,100 $\times$ 670 nm$^2$ ($\beta_s = -5 \text{ fs}^2 \text{ mm}^{-1}$, $\beta_i = 1,800 \text{ fs}^4 \text{ mm}^{-4}$), an amplification bandwidth exceeding 10 THz will become possible. Such a system
could exceed the C-band amplification bandwidth of EDFAs (black bar in Fig. 1b) by more than three times and can be fabricated on a chip of dimensions 5 x 5 mm.

The Si₃N₄ photonic chip used in this work is shown in Fig. 1a and a microscope image of the waveguide spiral is shown in Fig. 1e. Figure 1d depicts a scanning electron micrograph of the chip cross section, showing two parallel Si₃N₄ waveguide cores. The mode profiles of the fundamental transverse-electric modes (TE₀₀) are superimposed on the waveguide cores. We measure the spiral waveguide’s transmission spectrum (D63_03_F4_C11_WG1), dispersion profile and propagation loss with a customized, polarization-maintaining, scanning diode laser spectrometer and optical frequency-domain reflectometer in the wavelength range from 1,260 nm to 1,630 nm, calibrated using a self-referenced fibre-laser frequency comb. The measurement data and results are presented in Extended Data Fig. 2. The optical transmission through the 2-m-long spiral is measured to be as high as 12%, with
The transmission of the power-amplified pump laser is carefully optimized to 12%, in agreement with the calibrated transmission measurement at low optical power. The total fibre-to-fibre loss including the fibre-to-chip coupling losses (two facets) and optical propagation loss in the Si$_3$N$_4$ waveguide spiral is marked as grey dotted lines in Fig. 2b,d and reaches as low as 10 dB. 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 fibre–chip–fibre coupling losses. Furthermore, no damages of the waveguide and coupling facets are observed at input power levels up to 7 W. Notably, this gain and power level are sustained without any mitigation techniques for stimulated Brillouin scattering, such as fast pump laser dithering or phase modulation.

As depicted in Fig. 2b,d, the measured full bandwidths of gain and frequency conversion reach 20 nm, despite the notable anomalous GVD of our thick Si$_3$N$_4$ waveguide. The measurement results are commensurate with our numerical calculations as shown in Fig. 2c,e, using the full set of nonlinear equations in the frequency domain. Details of the numerical calculations can be found in Methods. Notably, the literature value widely cited for the Si$_3$N$_4$ nonlinear refractive index of $n_2 = 2.4 \times 10^{-19}$ m$^2$ W$^{-1}$ would result in a peak signal gain $G_s$ in excess of 18 dB. Recent measurements of the Si$_3$N$_4$ nonlinear refractive index show a reduced value of $n_2 = 2.2 \times 10^{-19}$ m$^2$ W$^{-1}$, probably owing to a reduced fraction of Si–Si and Si–H bonds in high-temperature grown
and annealed stoichiometric Si$_3$N$_4$ used for low absorption loss. We estimate the effective mode area $A_{	ext{eff}}$ as small as 1.67 $\mu$m$^2$ and the effective nonlinearity $\gamma$ of our waveguide as 0.51 W$^{-1}$ m$^{-2}$. With these parameters, our numerical calculations predict a peak gain of 12 dB, in good agreement with measurements. Fluctuations of the waveguide cross section that flatten and broaden the parametric gain lobes, and the remaining uncertainty around the transmission loss value$^{47}$, are negligible in the strong anomalous GVD regime of our waveguide.

As an independent check, we also measure the parametric gain by fast modulation of the pump laser. We modulate the pump laser amplitude with a 50-MHz square wave before amplification with a duty cycle of 50%. The instantaneous nature of parametric amplification mediated by the optical Kerr effect imprints the pump modulation directly on the amplified signal and generated idler. The measurement results are depicted in Fig. 3. The pump laser is tuned to 1,544.5 nm for this measurement, without the signal (red) is obtained from modulation instability of the strong pump laser and finite bandwidth of the bandpass filter used to reject the pump light. c. Measured optical signal gain extracted from the modulation measurement (blue). A simulated gain curve is depicted in red.

**Online content**

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Device fabrication
The Si₃N₄ photonic chips are fabricated using an optimized photonic Damascene process. The waveguide patterns are written by deep-ultraviolet stepper lithography based on a 248-nm KrF excimer laser. The advantages of using deep-ultraviolet stepper lithography instead of electron-beam lithography include smaller and fewer field stitching errors, easy implementation of multipass writing and high fabrication throughput. The patterns are dry-etched to the SiO₂ substrate to create waveguide preforms. The SiO₂ on silicon substrate is then annealed at 1,250 °C (preform reflow) to further reduce the root mean square roughness of the waveguide sidewalls to the sub-nanometre level. Thermal reflow of the Damascene preform reduces sidewall scattering loss by between 30% and 50% (ref. 36). Stoichiometric Si₃N₄ film of around 1 μm thickness is deposited on the patterned substrate by means of low-pressure chemical vapour deposition and filled the preform trenches to form the waveguide cores. An etchback planarization process, combining dry etching and chemical-mechanical planarization, is used to remove excess Si₃N₄ and create waveguide top surface with 0.3 nm root mean square roughness. Afterwards, the substrate is annealed at 1,200 °C with nitrogen atmosphere to drive out the residual hydrogen impurities in the Si₃N₄ film. A top SiO₂ cladding composed of tetraethyl orthosilicate and low-temperature oxide is deposited on the wafer, followed by SiO₂ annealing at 1,200 °C. The triple annealing strategy, that is, substrate reflow, Si₃N₄ anneal and SiO₂ top cladding anneal, facilitated by the photonic Damascene process, is key to the achievement of ultralow waveguide scattering and absorption loss. Finally, the wafer is separated into individual photonic waveguide chips by means of deep dry etching followed by backside grinding. Light is coupled into the waveguide facets as etched.

Numerical calculations of optical parametric gain
Numerical calculations of the signal gain Gₛ and idler frequency conversion Gᵢ, of the pump, signal and idler frequencies are performed using frequency-domain nonlinear coupled-mode equations of the complex power-normalized amplitudes Aₚ,S,I = √Pₚ,S,I of the pump, signal and idler, respectively,

\[
\frac{dAₚ}{dz} = (i(\gamma |Aₚ|^2 + 2 |Aₛ|^2 + 2 |Aᵢ|^2) - \alpha/2) \cdot Aₚ + iγ Aₛ Aᵢ e^{iΔβz},
\]

\[
\frac{dAₛ}{dz} = (i(2 |Aₚ|^2 + |Aₛ|^2 + 2 |Aᵢ|^2) - \alpha/2) \cdot Aₛ + iγ Aₚ Aᵢ e^{-iΔβz},
\]

\[
\frac{dAᵢ}{dz} = (i(2 |Aₚ|^2 + 2 |Aₛ|^2 + |Aᵢ|^2) - \alpha/2) \cdot Aᵢ + iγ Aₚ Aₛ e^{-iΔβz}.
\]

Herein, α denotes the linear propagation loss and γ denotes the effective nonlinearity of the silicon nitride waveguide γ = γₑ/nₑ, in which nₑ is the nonlinear refractive index of the waveguide core and Aₑ is the nonlinear effective mode area. Numerical simulations of waveguide dispersion are carried out in COMSOL in the range 100–400 THz and interpolated taking into account up to the 12th order of dispersion. The phase mismatch Δβ is calculated from the numerically simulated dispersion. The nonlinear coupled-mode equations are integrated using a forward Euler scheme along the waveguide spiral of length L and the signal gain and idler conversion efficiency are calculated relative to the input signal power Pₛ(0):

\[
Gₛ(L) = \frac{Pₛ(L)}{Pₛ(0)}, \quad Gᵢ(L) = \frac{Pᵢ(L)}{Pᵢ(0)}
\]

Past the breakthrough of achieving net gain off chip in a photonic-circuit-based travelling-wave optical parametric amplifier, it is obvious that there still exists a large performance gap between contemporary nonlinear fibre-based optical parametric amplifiers and photonic-circuit-based optical parametric amplifiers. Fibre-based optical parametric amplifiers are limited by fibre absorption and tight tolerance requirements to maintain close-to-zero anomalous dispersion along the fibre length. Hence it is interesting to extrapolate the potential performance of dispersion-engineered Si₃N₄ waveguides. In Extended Data Fig. 1, we perform this extrapolation up to the limit of absorption of Si₃N₄ waveguides fabricated with the photonic Damascene process at EPFL. Recent measurements by means of thermal response spectroscopy show an absorption loss of stoichiometric silicon nitride of 0.15 dB m⁻¹ at 1,550 nm with very weak contribution from Si–H and N–H bonds. Substituting this value into equation (3), we find that small signal gains in excess of 70 dB and close to the performance of fibre-based optical parametric amplifiers are realistic, if scattering loss can be reduced below the absorption limit. The results for a chip size of 5 × 5 mm², that is, maximum waveguide length 2.5 m and a chip size of 20 × 20 mm², that is, maximum waveguide length 30 m, are depicted in Extended Data Fig. 1a,b, respectively. We note that the absorption loss of 0.15 dB m⁻¹ could also be improved in the future using different Si₃N₄ and SiO₂ deposition methods. Last, we wish to point out the recent study by Gao et al., who showed that dispersion-engineered Si₃N₄ waveguides have a higher ratio of Kerr nonlinearity to absorption loss than contemporary waveguide systems based on SiO₂ and AlGaAs.

Characterization of waveguide spirals
We measure transmission, reflection, dispersion and propagation loss of metre-long Si₃N₄ waveguide spirals with a customized frequency-comb-calibrated scanning diode laser spectrometer. The optical setup and results for the waveguide spiral used in the experiment that was depicted in Fig. 2 are shown in Extended Data Fig. 2a. It is an extension of our earlier instrument for the characterization of integrated microresonator dispersion and loss. Three mode-hop-free, wideband-tunable, external-cavity diode lasers (Santec TSL-710) cover the wavelength ranges of 1,260–1,360 nm (green), 1,350–1,500 nm (red) and 1,500–1,630 nm (blue). They are operated in sequence to form a full laser scan from 1,260 to 1,630 nm. Regular calibration markers are recorded by filtering a beat note between the sweeping laser and a commercial optical frequency comb (Menlo OFC-1500) using a balanced photo receiver and logarithmic radio frequency detector (Analog Devices AD8307) for increased dynamic range. Furthermore, an imbalanced fibre-optic Mach–Zehnder interferometer and a molecular gas cell are used for further calibration and wavelength determination. More details can be found in refs. 50,51.

The transmission, reflection, an input power reference and optical frequency-domain reflectometry (OFDR) traces are recorded at the four ends of a three-way Mach–Zehnder interferometer formed by three polarization-maintaining (PM) 50/50 fibre beam splitters (OZ Optics). Light is coupled into and out of the photonic chip using PM lensed fibres (OZ Optics). The traces are digitized using an eight-channel analogue-to-digital converter oscilloscope. Calibration of the transmission is performed by recording a trace, in which the lensed fibres are replaced with a PM patch cord. Calibration of the spiral reflection trace is performed by replacing the input lensed fibre with a fibre-coupled PM retroreflector. Both calibrations are performed relative to the concurrently recorded input power reference channel. The calibrated transmission and reflection spectra of the spiral are depicted in Extended Data Fig. 2b,c, respectively. The colours in Extended Data Fig. 2 denote the three laser scans. We attribute the notable modulation of the measured transmission to the interferences from chip facet reflections, defect reflections and inter-modal interference, as discussed in the next section. We observe that the spiral transmits only in the 1.5–THz windows around 193 THz, 210 THz and 227 THz, at which the transmission reaches up to 12% and 10%, on average. Hence we attribute
a mean loss level of around 10 dB to the waveguide spiral in the relevant transmission window at 193 THz, as depicted in Fig. 2b, d. We attribute the existence of the transmission windows to a destructive interference of higher-order mode generation in the two straight-to-circular transitions of each identical 90° corner of our waveguide spirals as seen in Fig. 1e. Outside the transmission window, the light is coupled into higher-order modes in the spiral corners. An increase in reflection in those areas hints towards the increased coupling of higher-order modes to the nearest-neighbour arms of the spiral before dissipation. We estimate a coupling loss of about 4.5 dB, nearly fibre-to-fibre through the photonic chip, and conclude a linear propagation loss in the transmission windows of 2.75 dB m⁻¹.

The OFDR traces are analysed with segmented Fourier transform (see Extended Data Fig. 2d–f) using eight segments per trace (24 in total) with a window overlap equal to one segment. Our precise frequency-comb calibration entails that the distance axis of the measurement denotes the optical distance without the requirement to scale for a certain group velocity index or fibre interferometer reference, as is common with state-of-the-art OFDR instruments. The shading of the coloured OFDR traces indicates the centre frequency of a particular segment, with darker colour indicating a higher frequency. The propagation losses are estimated by linear fitting of the distance-dependent optical back-reflection, depicted as dotted orange lines in Extended Data Fig. 2d. The fit is performed over the region marked by vertical orange lines. In the centre of the spiral a broad scattering feature due to the coupling between neighbouring spiral arms is observed. Owing to an underlying frequency noise background caused by laser phase noise, we interpret the measured values as an upper bound. The extracted values for the optical propagation loss are depicted in Extended Data Fig. 2g. We observe a mean defect density of 2 m⁻¹. The group velocity dispersion βg is evaluated from the frequency-dependent optical length of the spiral, by identifying the main reflection peaks of the chip input and output facets. The physical length of the spiral is 2.0 m. Because the waveguide tapers are only 0.3 mm long, their contribution to the measured dispersion can be ignored. Owing to the higher-order mode coupling, we can only observe a sharp and coherent back-reflection peak in the three transmission windows to extract the group velocity dispersion βg, which we estimate as −134 fs² mm⁻¹.

Multimode interference in 90° waveguide bends

The emergence of periodic transmission windows in the metre-long rectangular spiral waveguide is tied to the interference of higher-order modes in the straight-to-circular transitions of the 400 identical 90° waveguide bends with radius 230 μm. Lorentz reciprocity demands that the scattering matrix between the fundamental and higher-order modes at the straight-to-circular transition is symmetrical and hence the amplitudes for higher-order mode excitation are equal both at the beginning and at the end of the waveguide bend. At certain frequencies, this will induce a destructive interference between the higher-order modes generated at both ends of the waveguide bend, preventing power loss to higher-order waveguide modes in each bend of the spiral. Away from the destructive interference frequencies, we observe much stronger waveguide losses and a chaotic and strongly modulated transmission. We calculate the optical angular frequency difference δω between successive destructive interference events from the phase difference Δθ between the fundamental (TE0) and higher-order (TEm) mode in the waveguide bend with radius R and group refractive index ngr.

\[
\Delta \theta = \frac{R \pi}{2c} (n_{g,10} - n_{g,00}) \Delta \omega \left( \frac{1}{2m+1} \right) \pi.
\]

The results are depicted in Extended Data Fig. 3. For our waveguide spiral, we calculate transmission window spacings of 14 THz around 202 THz and 16.5 THz around 220 THz, which is in good agreement with the observed values of 16 THz and 17.5 THz, respectively. Comparison with other higher-order-mode excitations such as the TE20 mode leads to much shorter frequency distances incommensurate with our observations.

Measurement of parametric gain and frequency-conversion spectra

The optical parametric gain spectra are determined as follows. Both the pump and signal lasers are derived from wideband, continuously tunable, external-cavity diode lasers (TOPTICA CTL). The pump laser is amplified using a high-power EDFA (Keopsys CEFA-C-HP-HP-43, maximum power 15 W). We filter the amplified spontaneous emission light using a tunable thin-film bandpass filter (FOF-02524323, insertion loss 2 dB) after the amplified pump light passes a high-power polarization-maintaining isolator (Advanced Fiber Resources HP-MI-55-20-2-1-F-P). We combine the pump and signal lasers on a 99/1 fused-fibre beam splitter. The high power output from the splitter carries most of the pump light, whereas the signal light is attenuated by −20 dB in the splitter and generally kept below −200 μW throughout all measurements presented here. We perform two separate wavelength scans with the signal laser, while the pump laser is kept at 1,535 nm. The first laser scan (Scan 1) is performed from the pump wavelength towards longer wavelength and the second scan (Scan 2) is performed towards lower wavelengths. The signal gain G_s and idler frequency-conversion efficiency G_i are related to the power at the signal of the output of the waveguide. We use the max hold function of the optical spectrum analyser to record the full gain spectra at each power level in a single, slow laser scan (about 30 s) at a resolution bandwidth of 2 nm. The signal transmission and fibre-to-chip coupling loss spectra are measured in an independent measurement to derive the on-chip gain (only propagation loss) and off-chip net gain (including fibre-to-chip coupling loss) conditions. We measure a transmission of the signal laser of −28 dB in the absence of gain and frequency conversion owing to the pump. The underlying raw data or measurement of the gain spectra are depicted in Extended Data Fig. 4.

Comparison of state-of-the-art TWOPAs using integrated photonics

The field of photonic integrated TWOPAs was initiated by the pioneering work of Foster et al. showing that a signal gain G_s of up to 4 dB can be achieved in a silicon waveguide despite two-photon absorption at the telecommunication wavelength in silicon. However, to achieve laser peak power as high as possible, a picosecond pulsed pump laser was required to dissipate the generated carriers in silicon before the next pulse and to not damage the waveguide with high average power. Yet, the goal of continuous-wave optical parametric gain in silicon waveguides remains elusive, despite the order-of-magnitude progress from the application of advanced concepts such as mid-infrared driving, the use of hydrogenated amorphous silicon and carrier depletion structures. In spite of all these efforts, continuous-wave gain could not be demonstrated. It remains dubious whether continuous-wave net gain in the near-infrared spectral range will be achieved in silicon waveguides, owing to the fundamental two-photon absorption effect and thermal damage of the waveguides.

This fundamental problem has spurred a whole field of research into new waveguide core materials with increased two-photon absorption thresholds, such as AlGaAs (ref. 44), ultra-silicon-rich nitride Si_N_x (ref. 45), GaP (ref. 46) and chalcogenide waveguides, to name a few. The main focus of these works is the improvement of the so-called nonlinear figure of merit, that is, the relation between the Kerr nonlinearity and the nonlinear absorption by careful balance of the electronic bandgaps and pump wavelengths. We believe that many of those platforms could, at some point in the future, achieve the continuous-wave parametric gain breakthrough with sufficient improvements of fabrication quality and yield. The contemporary performances of these platforms are detailed in Extended Data Table 1. The figure of merit of the reported devices is defined as the ratio between the signal gain in decibel and the pump peak power. We also estimate the total signal gain and idler conversion...
efficiency from the values reported in the literature, while summing the reported losses from propagation and two fibre-to-chip coupling junctions. However, we wish to point out two things: (1) these materials are, at this time, considered ‘exotic’ in the photonic integrated circuit community and might need a long time to become available through foundry service and (2) the ultralow loss and high power tolerance in modern Si$_3$N$_4$ waveguides so far outperforms even those photonic-integrated circuit platforms in terms of the relationship of Kerr nonlinearity and optical absorption\(^5\). Given then the increased confinement and nonlinearity in these 'third-generation' waveguide materials, we believe that these materials, at their respective fundamental absorption limits, might outperform Si$_3$N$_4$ in terms of optical gain bandwidth and compactness. However, continuous wave net gain on chip or off chip has not been realized so far, which is mostly owing to the increased scattering and absorption losses of high-index materials and the difficulty coupling broadband light into high-index waveguides clad with air or silica, whose refractive index is much lower. Simultaneously, high-confinement Si$_3$N$_4$ waveguides were developed following the pioneering works of Gondarenko et al.\(^5\) and Levy et al.\(^\) that overcome the high tensile stress of stoichiometric low-pressure chemical vapour deposition Si$_3$N$_4$ and achieved the required waveguide core thickness for anomalous group-velocity dispersion. High waveguide scattering losses precluded the application of these early Si$_3$N$_4$ waveguides in TWOPAs. Driven by the desire to reduce the parametric oscillation threshold in optical microresonators, Si$_3$N$_4$ waveguide losses have been reduced by more than 1.5 orders of magnitude in the last decade, which now allows Si$_3$N$_4$-based TWOPAs operated with continuous-travelling-wave pump and net gain on chip and off chip for the first time with a 100-fold increase in the figure of merit.

Data availability

The code and data used to produce the plots are found on the Zenodo repository https://doi.org/10.5281/zenodo.6989024.
Extended Data Fig. 1 | Numerical calculations of maximum (small) signal gain as a function of waveguide loss and length. a, For a waveguide of cross section dimensions 2,450 nm × 910 nm and pump power of 4 W, as used in this study. The dotted grey lines represent the threshold for on-chip parametric gain. b, For optimized waveguide cross section of 2,100 nm × 670 nm using 0.75 W of pump power. The lowest waveguide loss value of 0.15 dB m⁻¹ represents the waveguide absorption loss of Si₃N₄ structures fabricated using the photonic Damascene process at EPFL.
Extended Data Fig. 2 | Frequency-comb-calibrated characterization of waveguide spirals. a, Optical setup. See text for description. b, Calibrated transmission spectrum through a spiral. The trace colours indicate the three individual external-cavity diode laser scans. c, Calibrated reflection spectrum inside and from a spiral. d, OFDR traces are analysed using segmented Fourier transformation and vertically offset by 15 dB. The shading indicates the centre frequency according to panel e. The propagation loss fitting region is marked with vertical orange lines. The propagation loss is determined from the dotted line fit. e, Propagation loss extracted from OFDR. Extracted propagation losses are relative to optical distance and must be multiplied by the group index of 2.08 for conversion to the physical waveguide length. The values represent upper bounds owing to a background of laser phase noise that induces an increased gradient. f,g, Zooming into OFDR traces around the front (f) and back (g) facets. Dots depict successful identification of backside facet reflection for valid dispersion measurement. h, Inverse group velocity \( \beta \) as a function of wavelength. Markers correspond to f,g. The black line indicates the fitted waveguide dispersion curve up to the third order.
Extended Data Fig. 3 | Mode mixing and interference in rectangular waveguide spirals. a, Schematic indication of a typical 90° waveguide bend in a rectangular spiral. All bends are identical and have a radius of 230 μm. Insets show the normalized mode profile for the TE₀₀, TE₁₀ and TE₂₀ modes.

b, Simulated group refractive indices for the TE₀₀, TE₁₀ and TE₂₀ modes of a 2.45 μm × 0.91 μm strip waveguide with vertical sidewalls. c, Calculated spectral frequencies for destructive interference between higher-order mode excitation at the beginning and at the end of the waveguide bend.
Extended Data Fig. 4 | Raw data of gain spectrum measurement. See the main text for detailed description.
**Extended Data Table 1 | Comparison of the state-of-the-art, photonic-integrated-circuit-based TWOPAs and frequency converters**

| Ref. | Material | Year | $\lambda_P$ (nm) | $\gamma$ (Wm$^{-1}$) | $\alpha$ (dB) | $\alpha_{tot}$ (dB) | $G_S$ (dB) | $G_I$ (dB) | $P_{pk}$ (W) | $D$ (%) | FOM (dB W$^{-1}$) |
|------|----------|------|------------------|----------------------|--------------|------------------|----------|----------|--------------|--------|----------------|
| 7    | Si       | 2006 | 1,550            | 155                  | $-120$       | $-26$            | 5        | 4        | 11           | 0.03   | 0.45          |
| 9    | Si       | 2011 | 2,173            | 150                  | $-280$       | $-26$            | 50       | 50       | 13.5         | 0.02   | 3.7           |
| 15   | Si       | 2012 | 1,542            | 200                  | $-200$       | $-18$            | 5        | 3        | 0.4          | CW     | 12.5          |
| 11   | a-Si:H   | 2015 | 1,550            | 0.64                 | $-35$        | $-19$            | 12       | 10.5     | 0.75         | 0.16   | 16            |
| 8    | As$_2$S$_3$ | 2008 | 1,532            | 9.9                  | $-50$        | $-17$            | 32.5     | 30.6     | 9.6          | 0.003  | 3.3           |
| 13   | Si$_7$N$_3$ | 2017 | 1,550            | 500                  | $-45$        | $-17$            | 42.5     | 36.2     | 14           | 0.001  | 3.0           |
| 12   | AlGaAs   | 2018 | 1,550            | 630                  | $-200$       | $-6.4$           | 1.4      | $-4.2$   | 0.4          | CW     | 3.5           |
| 17   | PPLN     | 2016 | 1,550            | 300                  | —            | 1.2              | 12.8     | 12.5     | 1.38         | CW     | 9.3           |
| 57   | Si$_3$N$_4$ | 2011 | 1,550            | 1.15                 | $-50$        | $-9$             | 3.8      | 2        | 24           | 1      | 0.16          |
| This work | Si$_3$N$_4$ | 2021 | 1,555            | 0.50                 | $-3$         | $-1.5$           | 12       | 9        | 4.7          | CW     | 2.6           |

$\alpha$: linear optical propagation loss; $\alpha_{tot}$: total loss including coupling from and to optical fibres; $\gamma$: effective Kerr nonlinearity; $\lambda_P$: pump wavelength; CW: continuous wave; $D$: pump pulse duty cycle; FOM: material-independent figure of merit, $G_I/P_{pk}$; $G_S$: frequency-conversion efficiency relative to signal output; $G_I$: on–off signal gain (phase insensitive); $P_{pk}$: peak pump power. Refs. 7--9, 11--13, 15, 17, 57.