Optically reconfigurable quasi-phase-matching in silicon nitride microresonators

Edgars Nitiss\textsuperscript{1,3}, Jianqi Hu\textsuperscript{1,3}, Anton Stroganov\textsuperscript{2} and Camille-Sophie Brè\textsuperscript{3}•\textsuperscript{1}

Quasi-phase-matching has long been a widely used approach in nonlinear photonics, enabling efficient parametric frequency conversions such as second-harmonic generation. However, in silicon photonics the task remains challenging, as materials best suited for photonic integration lack second-order susceptibility ($\chi^{(2)}$), and means for achieving momentum conservation are limited. Here we present optically reconfigurable quasi-phase-matching in large-radius silicon nitride microresonators, resulting in up to 12.5-mW on-chip second-harmonic generated power and a conversion efficiency of 47.6% W\textsuperscript{-1}. Most importantly, we show that such all-optical poling can occur unconstrained from intermodal phase-matching, leading to broadly tunable second-harmonic generation. We confirm the phenomenon by two-photon imaging of the inscribed $\chi^{(2)}$ grating structures within the microresonators as well as by in situ tracking of both the pump and second-harmonic mode resonances during all-optical poling. These results unambiguously establish that the photogalvanic effect, responsible for all-optical poling, can overcome phase mismatch constraints, even in resonant systems.
of an intracavity pump and SH gives rise to a self-organized space charge grating along the direction of light propagation. This is confirmed experimentally by imaging the inscribed nonlinear grating structures with two-photon (TP) microscopy. The images also allow the unambiguous identification of interacting SH modes based on the measured grating periods and shapes. We observe that multiple SH modes can participate in the AOP process without azimuthal mode number matching. Therefore, SH generation in the AOP Si$_3$N$_4$ microresonator is unconstrained from the perfect phase-matching condition, substantially simplifying its design and allowing for unprecedented device performance based on QPM. With relatively small free spectral range (FSR) microresonators, we are able to optically reconfigure the $\chi^{(2)}$ gratings for SH generation in multiple pumped resonances. Our devices could output up to 12.5 mW of SH power on-chip with CE values reaching 47.6% $\text{W}^{-1}$. Moreover, we introduce an in situ technique that simultaneously probes pump and SH resonance detunings during the AOP event. We observe that, once the $\chi^{(2)}$ grating is inscribed, it is self-sustained and even enhanced when the pump is further detuned, albeit the SH resonance walks off. This enables remarkable SH wavelength tuning capability within one pump resonance. The demonstrated results provide new insights towards achieving complete $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities on CMOS-compatible platforms.

**Results**

**AOP of Si$_3$N$_4$ microresonators.** Figure 1a presents a schematic illustration of photo-induced QPM for SH generation in Si$_3$N$_4$ microresonators. By launching the fundamental transverse electric (TE) mode of the pump from the bus waveguide into the microresonator, AOP inscribes an intracavity QPM grating, which subsequently ensures efficient SH at the output. The doubly resonant condition sets the prerequisite for initiating AOP, as detailed in Fig. 1b. The pump wavelength $\lambda_p$ is initially set on the blue side of the cold pump resonance $\lambda_{cP}$, while the virtual SH wavelength $\lambda_{SH} = \lambda_p/2$ is expected to be on the red side of a particular SH mode resonance $\lambda_{SH}$ (region I). As the pump is red-detuned closer to the pump resonance, both pump and SH resonances would also be redshifted due to the thermal and Kerr effects in the microresonator (region II). It is important to note that the SH resonance redshifts faster than that of the pump (Supplementary Note 1). As a consequence, the pump and SH resonances eventually match with $\lambda_p$ and $\lambda_{SH}$, respectively; that is, the pump and SH become doubly resonant (region III). A seed SH signal then efficiently initiates the photogalvanic effect, leading to photo-induced QPM and SH generation. A remarkable feature of the device manifests itself once the pump wavelength is further red-detuned. Despite the walk-off of the SH resonance and deviation from the ideal QPM condition, efficient SH generation is still maintained (region IV). The generated SH and the intracavity $\chi^{(2)}$ grating form a dynamic equilibrium by means of self-sustaining feedback.

Figure 1c presents an artistic representation of the inscribed $\chi^{(2)}$ gratings (not the exact number of periods, due to illustration purpose) for the 146-GHz microresonator we used in the study, along with the simulated spatial mode profiles at the SH wavelength (Supplementary Note 1). These are based on the interactions between the fundamental TE mode at the pump (FH1) and the first five TE$_{0n}$ ($n = 0, 1, 2, 3, 4$) modes at the SH (denoted SH1 to SH5). The inscription of the self-organized $\chi^{(2)}$ gratings bypasses the need for perfect phase-matching. Regardless of the resonating SH mode in AOP, the QPM grating automatically compensates the phase mismatch between the involved pump and SH modes. As will be shown later, the doubly resonant condition implies an integer number of grating periods inscribed in the microresonator. This is experimentally observed in Fig. 1d using the TP imaging technique. By superimposing a number of depth-scanned measurements, we are able to reconstruct the TP image of the entire 146-GHz microresonator poled at 1,543.00 nm. Here 11 QPM periods are clearly recognizable. Figure 1d also serves as a direct proof of photo-induced QPM in Si$_3$N$_4$ microresonators.

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**Fig. 1 | Diagram of photo-induced quasi-phase-matching in Si$_3$N$_4$ microresonators.** a, Illustration of SH generation by AOP. The fundamental TE mode of the pump FH1 ($\omega$) inside the waveguide is coupled to the microresonator. AOP inscribes a nonlinear grating on the circumference of the microresonator and provides QPM for efficient SH ($2\omega$) generation. b, Dynamics of the AOP process. $\lambda_p$, pump wavelength; $\lambda_{SH}$, SH wavelength; $\lambda_{cP}$, pump resonance wavelength; $\lambda_{cSH}$, SH resonance wavelength. In region I neither pump nor SH is resonant. In region II, as $\lambda_p$ is tuned into pump resonance $\lambda_{cP}$ (resonant for pump), both $\lambda_p$ and $\lambda_{SH}$ redshift due to the thermal and Kerr effects, compensating the mismatch between the virtual $\lambda_{cP}$ and $\lambda_{SH}$ (still not resonant for SH). In region III, once being doubly resonant for pump and SH, efficient AOP takes place. A nonlinear grating is inscribed and SH is generated. An experimentally obtained TP image of the entire microresonator, reconstructed from the superposition of several depth-scanned TP measurements. Eleven QPM grating periods are clearly recognized in the 146-GHz microresonator poled at 1,543.00 nm.
When the laser scans over a pump resonance from blue to red, we record the pump transmission and SH power on-chip (Fig. 2b) as well as their resonance detunings (Fig. 2c). Before the pump enters the pump resonance (region I) and before the seed SH light is resonantly enhanced (region II), no SH signal is generated. Once being doubly resonant (region III), we observe a sharp rise in SH signal, indicating that the AOP is initiated, here for a pump wavelength around 1,548.60 nm. For this particular resonance, the $\chi^{(2)}$ grating results from the interference of the fundamental TE mode at the pump and the second TE mode at the SH (SH2), as inferred by TP imaging. The SH generation is then maintained until the pump is tuned out of its resonance (region IV). To gain insight into this behaviour, we apply the aforementioned method to track the detunings of both resonances. Figure 2c illustrates the normalized VNA responses at different wavelengths. After AOP occurs, we observe two peaks in the measured transfer functions, which respectively correspond to pump and SH resonances (Supplementary Note 2). During the wavelength sweep, the positions of the peaks shift according to the detunings of the pump and SH resonances. The peak closer to the d.c. response indicates the pump resonance, while the other peak indicates the SH resonance. Noticeably, the SH continues to be generated even when the SH resonance has greatly moved away from the SH wavelength. The VNA response maps for some other resonances are provided in Supplementary Note 3.

Reconfigurable QPM and grating imaging. Figure 3a illustrates versatile AOP of the 146-GHz microresonator in the wavelength range between 1,540 nm and 1,561 nm. When the wavelength sweep is performed without external temperature control ($T = T_{\text{room}}$), 11 out of the 18 available resonances show occurrences of AOP. By leveraging thermal control, the relative frequency offsets between the pump resonances and various SH mode resonances can be effectively modified. For example, when the chip holder temperature is stabilized at $T = 45^\circ \text{C}$, some additional resonances can support SH generation. The AOP is enabled by the highly flexible doubly resonant condition between the fundamental pump mode and several SH modes. Such a doubly resonant condition with detuning terms is given by

$$\frac{2\pi n_{\text{eff,a(b)}}}{\lambda_{\text{P(SH)}}} 2\pi R = 2\pi m_{a(b)} - \theta_{a(b)}$$

(1)

where $R$ is the radius of the microresonator and $n_{\text{eff,a(b)}}$ and $\theta_{a(b)}$ are the effective refractive indices, azimuthal mode numbers and phase offsets of the pump and SH modes, respectively. For pump and SH wavelengths in the vicinity of their corresponding resonances we have $|\theta_{a(b)}/2\pi| \ll 1$. The phase offsets can be expressed as $\theta_{a(b)} = \theta_{a(b)}/\Delta_{\text{FSR,a(b)}}$, where $\Delta_{\text{FSR,a(b)}}$ represents the effective detunings in angular frequency. Besides being doubly resonant, the phase-matching condition is also required in the SH generation process. The phase mismatch between the pump and SH is given by

$$\Delta k = \frac{2\pi n_{\text{eff}}}{\lambda_{\text{SH}}} - \frac{2\pi n_{\text{eff}}}{\lambda_{\text{P}}} = m_{\text{b}} - \frac{m_{\text{a}}}{R} - \frac{\theta_{\text{b}} - 2\theta_{\text{a}}}{2\pi R}$$

(2)
The χ\(_{2}\) grating occurs when phase offsets satisfy \(\Delta k = 2\pi \Delta \rho / \Lambda\), where Λ is the grating period. The χ\(_{2}\) grating structure follows the interference of pump and SH fields:

\[
\chi^{(2)}(\phi) \sim \left( E_p^* \right)^* E_{SH} \exp(i \Delta k R \phi) + E_p^* E_{SH} \exp(-i \Delta k R \phi)
\]

where \(E_p\) and \(E_{SH}\) are the optical fields at the pump and SH, respectively. \(\phi\) denotes the azimuthal angle with reference to the centre of a microresonator, and * stands for complex conjugate. Notably, when phase offsets satisfy \(\theta_a = 2\theta_b\), an integer number of grating periods \(N = 2\pi R/\Lambda = m_b - 2m_a\) is inscribed on the circumference of the microresonator.

To reveal the χ\(_{2}\) gratings we image the poled microresonators using a TP microscope (Methods). Such a technique has previously been applied to capture the χ\(_{2}\) response in poled optical waveguides\(^{26,27}\). We observe the formation of versatile χ\(_{2}\) gratings by performing TP imaging of microresonators poled at various resonances. Figure 3b shows several retrieved grating structures along the circumference of the 146-GHz microresonator after coordinate transformation (Supplementary Note 4). By spatially resolved Fourier analysis we also acquire the spatial frequency graphs (Supplementary Note 4), allowing for precise identification of the grating periods and shapes. The observed χ\(_{2}\) grating periods are the result of the interaction between the fundamental pump mode and various SH modes. To unambiguously account for the participating SH modes, the grating periods and shapes are simulated as displayed in Fig. 3c. By comparing the experimental and simulated grating images we are able to identify the possible interacting SH modes from the fundamental SH mode (SH1) up to the fifth SH mode (SH5). AOP via SH modes higher than SH5 is not experimentally observed, which may be attributed to the increased total losses, resulting in insufficient SH enhancement for initiating the photogalvanic effect.

Occasionally, we also observe two distinct χ\(_{2}\) gratings subsequently inscribed within the same pump resonances, for example, the resonances near 1,552.0 nm and 1,553.2 nm as indicated in Fig. 3a. For these cases, SH generation is initiated by the resonant condition of one SH mode and is then taken over by another SH mode with further laser detuning. This is verified by imaging the χ\(_{2}\) grating structures and can also be inferred from the VNA measurements (Supplementary Note 3).

**SH generation bandwidth and χ\(_{2}\) grating characteristics.** A remarkable feature of photo-induced SH generation in microresonators is its unusual bandwidth. Figure 4a–d shows AOP of the 146-GHz microresonator at a particular pump resonance near 1,542.8 nm. The on-chip pump transmission (Fig. 4a) and generated SH power (Fig. 4b) are recorded at different pump power levels
during the AOP event. As expected, the pump thermal triangle is prolonged at high pump power due to the thermal-induced pump resonance drag. Moreover, once AOP is initiated, we observe the exceptionally broad spectral bandwidth over which SH generation can be maintained. At the highest pump power we measure a 10-dB SH generation bandwidth as large as 605 pm. Figure 4c depicts the VNA map measured with 22.2-dBm on-chip pump power, which corresponds to the dashed curves in Fig. 4a,b. Both pump and SH resonance detunings are clearly observed in the measured VNA responses. This confirms again that AOP can be effectively sustained despite a large walk-off of the SH resonance. To understand this behaviour, we characterize the $\chi^{(2)}$ strength inside the microresonator at different detunings (Supplementary Note 5), as shown in Fig. 4d. Counter-intuitively, we find that the measured $\chi^{(2)}$ is weakest immediately after the initiation of AOP, that is, when the pump and SH are doubly resonant. When the SH resonance gradually walks off from the generated SH wavelength, the strength of $\chi^{(2)}$ is enhanced. The inscribed $\chi^{(2)}$ then reaches an equilibrium that depends on the magnitude of the photogalvanic current and waveguide material conductivity. This explains, in part, the ultra-broad SH generation bandwidth in the AOP process, yet the full theoretical model describing the doubly resonant AOP still needs further investigation.

Given the FSR difference between the fundamental pump mode and the SH mode (Supplementary Note 1), the interaction of the same pump–SH mode pair can be matched several times within the pump sweep in the telecom band (Fig. 3a). However, for a specific pump–SH mode pair, the mismatch of the participating azimuthal mode numbers $m_a - 2m_b$ is not identical throughout the sweep. Hence, the number of $\chi^{(2)}$ grating periods $N = |m_a - 2m_b|$ inscribed inside the microresonator should vary accordingly. Using TP imaging we confirm such changes at different pump resonances in the 146-GHz microresonator. In particular, we study the fundamental pump mode–SH4 pair because of the large resulting QPM period. We experimentally identify three such AOP occurrences, which take place at 1,542.90 nm, 1,549.10 nm ($T = 45^\circ$C) and 1,559.35 nm. The inscribed $\chi^{(2)}$ grating structures at these wavelengths are recorded in Fig. 4e, with extracted grating periods of 90.1 μm, 80.6 μm and 70.7 μm, respectively. As shown in Fig. 4f, the retrieved grating periods are in excellent agreement with the simulated periods, considering fabrication tolerances. They roughly correspond to 11, 12 and 14 periods of QPM gratings in the microresonator, calculated based on $N = 2\pi R/\Lambda$. The slight discrepancy from integer numbers is probably due to the imprecision of the grating period measurement. Notably, the 11 grating periods estimated at 1,542.90 nm match exactly the number of periods directly observed in Fig. 1d (obtained at the same resonance but slightly different detuning). The FSRs at the fundamental pump mode and SH4 are simulated to be 145.7 GHz and 131.9 GHz, respectively (Supplementary Note 1). If we denote the participating azimuthal mode numbers at 1,542.90 nm as ($m_a', m_b'$), we can deduce from the simulated FSRs that the azimuthal numbers involved at 1,549.10 nm and 1,559.35 nm are ($m_a' - 5$, $m_b' - 11$) and ($m_a' - 14$, $m_b' - 31$), respectively. The relative changes in the azimuthal number differences $m_a' - 2m_b'$ are consistent with the retrieved number of QPM periods.

**Performance of SH generation in Si$_3$N$_4$ microresonators.** The performance of photo-induced SH generation in Si$_3$N$_4$ microresonators is illustrated in Fig. 5. To initiate AOP, the pump and SH need to be doubly resonant. As the pump and SH resonances show distinct thermal shifts (Supplementary Note 1), the initial mismatch between them can be effectively compensated during the thermal-induced resonance drag at the pump. Therefore, with higher pump power, the probability of the occurrence of AOP also increases with the extended thermal triangle. This is demonstrated experimentally in 146-GHz and 196-GHz Si$_3$N$_4$ microresonators, as shown in
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Discussion

A comprehensive comparison of state-of-the-art microresonator platforms for SH generation is summarized in Table 1. The ultra-broad bandwidth demonstrated in AOP of Si$_3$N$_4$ microresonators allows for tunable SH generation within a pump resonance, which is unparalleled by most of the other microresonators. Because our devices are not optimized for out coupling at the SH, the on-chip CE is limited compared to $\chi^{(2)}$ microresonators based on LN$^{9,11}$ and AlN$^{12,13}$. Still, our devices were able to output the highest SH power among the platforms. Such high-power and tunable SH generation is favoured in many practical applications, such as $f-2f$ self-referencing of Kerr combs on-chip$^{41,42}$. Most importantly, the automatic QPM in AOP greatly facilitates the SH generation in Si$_3$N$_4$ microresonators. In the experiment, we could easily inscribe and reconfigure the self-organized $\chi^{(2)}$ gratings for nearly all the pumped resonances. This is in stark contrast with the delicate intermodal phase-matching$^{12,13,15,23,43}$ and $\delta$-QPM$^{44,45}$ or the complex poling achieved by high-voltage sources$^{46}$ required in other platforms. Also, as highlighted by the bold entries in Table 1, the recent progress made for SH generation in integrated silicon photonic platforms$^{7,11,44,46}$ should not be overlooked. Undeniably, Si$_3$N$_4$ stands out as the most promising candidate in nearly every aspect of resonant SH generation. Besides the recent demonstration of ultra-high CE$^1$, we address in this work the unique benefit of extremely flexible photo-induced QPM in Si$_3$N$_4$ microresonators. These findings tend to indicate that past works on SH generation$^{33}$ (or SH combs$^{41,42}$ in Si$_3$N$_4$ microresonators) are most likely due to QPM instead of intermodal phase-matching, unless specifically designed for exact matching of azimuthal mode numbers.

In this study we explore the AOP of 146-GHz and 196-GHz Si$_3$N$_4$ microresonators for SH generation. Leveraging small FSR and overmoded microresonators, AOP is easily induced in multiple pumped resonances. Temperature and pump power controls offer additional degrees of freedom for optimizing the doubly resonant condition. Although the AOP threshold could be lowered and efficiency increased by using microresonators with larger FSRs$^{44}$, the possibility of AOP is substantially reduced. Therefore, given the recent development of Si$_3$N$_4$ microresonators with high Q values and small FSRs$^{44,45}$, we clearly envision SH generation with combined ultra-high CE and poling probability in small-FSR designs. Under such conditions, SH may be generated for every single resonance in an ultrafine FSR grid, thanks to automatic QPM rather than intermodal phase-matching. From our various VNA measurements, we also note that AOP could take place prior to the exact detuning condition mediated by the integer number of grating periods, that is $\theta_2 = 2\delta_2$ or $\delta_2 \approx 2\delta$. We even observe AOP when the fundamental SH resonance is at the blue side of the generated SH ($\delta_1 > 0$ and $\delta_2 < 0$), as shown in Supplementary Note 3. These observations provide important insights into the detuning information at AOP initiation, being slightly in advance of the exact QPM condition. Also, the optically inscribed $\chi^{(2)}$ in microresonators is characterized to be detuning-dependent, with the maximum measured value reaching ~0.03 pm V$^{-1}$ for the pump and SH4 interaction. This value is indeed smaller than another reported $\chi^{(2)}$ value (~0.2 pm V$^{-1}$) in Si$_3$N$_4$ microresonators$^{46}$ and the typical $\chi^{(2)}$ in Pockels materials$^{25,27}$. It should therefore be possible to further enhance the photo-induced $\chi^{(2)}$ to approach the fundamental limit predicted by the breakdown

![Fig. 5](https://www.nature.com/featureimages/Fig5.png)
In conclusion, we have demonstrated versatile SH generation on-chip CE, introducing more strengths. We have also implemented an in situ method for tracking the interacting resonance (2) and χ(3) nonlinearities in SiN microresonators will trigger new nonlinear applications in CMOS-compatible platforms. Pockels materials, the combination of χ(2) and χ(3) nonlinearities in SiN microresonators will trigger new nonlinear applications in CMOS-compatible platforms.

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Table 1 | Comparison of state-of-the-art microresonator platforms for SH generation

| Platform | 10-dB bandwidth | On-chip CE (% W−1) | On-chip SH power | Phase-matching (PM) condition |
|----------|----------------|-------------------|----------------|-----------------------------|
| LN4      | NA             | 90                | 22.5 μW        | QPM (electric-field poling) |
| LN5      | NA             | 230,000           | 2.1 μW         | QPM (electric-field poling) |
| LN6      | 1.9 pm         | 250,000           | 0.1 mW         | QPM (electric-field poling) |
| LN7      | 0.4 pm         | 5,000,000         | 20 μW          | QPM (electric-field poling) |
| AlN8     | 418 pm         | 2,500             | 3.2 mW         | Intermodal PM |
| AlN9     | NA             | 17,000            | 10 mW          | Intermodal PM |
| GaN10    | NA             | 0.015             | 2.2 μW         | Intermodal PM (claimed) |
| GaN11    | 200 pm         | 0.0002            | 2.4 pW         | Intermodal PM |
| GaAs12   | 300 pm         | 5                 | 0.6 nW         | Τ-PM |
| GaAs13   | 20 pm          | 100               | 13 μW          | Τ-PM |
| AlGaAs14 | 4,000 pm       | 0.07              | 5 nW           | Τ-PM |
| GaP15    | NA             | 44                | 47 nW          | Τ-PM |
| GaP16    | NA             | 400               | 25 μW          | Τ-PM |
| SiO217   | 13 pm          | 0.049             | 6 nW           | Intermodal PM |
| SiC18    | NA             | 360               | 1 μW           | Intermodal PM |
| SiN219   | NA             | 0.1               | 0.1 mW         | Intermodal PM (claimed) |
| SiN220   | 60 pm          | 2,500             | 2.2 mW         | Intermodal PM |
| SiN221   | 605 pm*        | 47.6              | 12.5 mW        | Reconfigurable QPM |

NA, data not available. The best values extracted from references are shown. Bold entries refer to typical silicon photonic platforms. Bandwidth for a single pump resonance. SH generation is achieved for 14 out of 18 resonances in the telecom band.
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Methods

Optical poling and detuning measurement set-ups. In our set-up, a tunable telecom-band c.w. laser was polarization-controlled and amplified using an erbium-doped fibre amplifier (EDFA). The amplified pump was aligned at TE polarization and injected into the bus waveguide of a Si$_3$N$_4$ microresonator using a lensed fibre. The input coupling loss was estimated to be 2.4 dB. At the output of the chip, both the residual pump and the generated SH were collected using a microscope objective before being separated by a dichroic beamsplitter and directed to their respective photodetectors (PD1 and PD2).

To measure the effective detunings of both pump and SH resonances, the c.w. laser was first weakly phase-modulated in an EOM before amplification. The applied modulation signal was a sweeping microwave tone from the VNA that scanned from 5 kHz to 1.5 GHz. Two weak optical sidebands were thus created at the pump wavelength, amplified together with the pump, and coupled to the microresonator. Part of the generated light at the SH was tapped to a reflective collimator and then directed to an a.c.-coupled fast silicon photodetector (PD3) with 1-GHz bandwidth. Finally, the retrieved microwave signal was sent back to the VNA. It is noted that, although our probing method resembles that in ref. 50, the fundamental difference is the use of the photodetector at the SH wavelength rather than the pump wavelength. Under such a configuration, no signal is detected before AOP occurs. When the $\chi^{(2)}$ is inscribed, in addition to SH generation, there is also sum-frequency generation between the sidebands and pump. Eventually, the beating between the sum-frequency components and the SH component gives the VNA response. The transfer function in VNA was found to reflect the detuning information of both the pump and SH resonances (Supplementary Note 2).

$\chi^{(2)}$ grating imaging and estimation. The inscribed $\chi^{(2)}$ gratings in the poled microresonators were measured with a TP microscope (Leica LSM 710 NLO) in an upright configuration. A He-Ne laser operating at 633 nm was used for microscope alignment. For excitation of SH in poled microresonators we used a Ti:sapphire laser (Coherent Chameleon Ultra II IR) producing 1,010-nm horizontally polarized light relative to the image plane. In the measurement, the focal point was raster-scanned across the sample in the grating plane and then its generated SH signal was recorded. The measured grating shape was slightly distorted in regions where the waveguide tangent was not perpendicular to the incident light polarization. The optical resolution of the obtained TP images was estimated to be 310 nm. These images were then replotted in the radial and tangential coordinates of the microresonators (Supplementary Note 4), as shown in Fig. 3b. As such, the $\chi^{(2)}$ grating periods could be extracted easily (their spatial frequencies are shown in Supplementary Note 4). The $\chi^{(2)}$ values in the poled microresonators were estimated based on a comparison with the calibrated $\chi^{(2)}$ in a poled waveguide (Supplementary Note 5).

Data availability

The data that support the plots within this paper are available at https://doi.org/10.5281/zenodo.5578073. Supplementary Information data are available from the corresponding author upon reasonable request.

Code availability

The codes used to produce the results of this paper are available at https://doi.org/10.5281/zenodo.5578073.

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Author contributions

E.N. and J.H. designed and performed the experiments, developed the theoretical analysis and simulations, and processed and analysed data. A.S. fabricated the Si$_3$N$_4$ samples. E.N., J.H. and C.-S.B. wrote the manuscript. The project was supervised by C.-S.B.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Camille-Sophie Brès.

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