Compact, spatial-mode-interaction-free, ultralow-loss, nonlinear photonic integrated circuits

Xinru Ji1, Junqiu Liu1✉, Jijun He1, Rui Ning Wang1, Zheru Qiu1, Johann Riemensberger1 & Tobias J. Kippenberg1✉

Multi-mode waveguides are ubiquitously used in integrated photonics. Although interaction among different spatial waveguide eigenmodes can induce novel nonlinear phenomena, spatial mode interaction is typically undesired. Adiabatic bends, such as Euler bends, have been favoured to suppress spatial mode interaction. Here, we adapt and optimize Euler bends to build compact racetrack microresonators based on ultralow-loss, multi-mode, silicon nitride photonic integrated circuits. The racetrack microresonators feature a footprint of only 0.21 mm² for 19.8 GHz free spectral range, suitable for tight photonic integration. We quantitatively investigate the suppression of spatial mode interaction in the racetrack microresonators with Euler bends. We show that the low optical loss rate (15.5 MHz) is preserved, on par with the mode interaction strength (25 MHz). This results in an unperturbed microresonator dispersion profile. We further generate a single dissipative Kerr soliton of 19.8 GHz repetition rate without complex laser tuning schemes or auxiliary lasers. The optimized Euler bends and racetrack microresonators can be building blocks for integrated nonlinear photonic systems, as well as linear circuits for programmable processors or photonic quantum computing.

1 Institute of Physics, Swiss Federal Institute of Technology Lausanne (EPFL), CH-1015 Lausanne, Switzerland. ✉email: liujq@iqasz.cn; tobias.kippenberg@epfl.ch

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Over the past decade, integrated photonic technology has been successfully translated from laboratory research into industrial applications, and has impacted today’s optical communication networks. Besides silicon—the backbone of microelectronic material, many new material platforms have been developed, as well as heterogeneous and hybrid integration techniques to merge them with silicon. Among these materials, amorphous silicon nitride (Si$_3$N$_4$)—first proposed in 1980—has been widely used in integrated nonlinear photonics. The large waveguide microresonator that features high-quality factor $Q$ and highly over-moded waveguides is uncontrollable, yielding spectrally monomeric generation is facilitated by employing phase matching (GVD) and ultralow optical losses near 1 dB m$^{-1}$. Combining with its high Kerr nonlinearity, weak Brillouin scattering, and negligible two-photon absorption, Si$_3$N$_4$ has become the material of choice particularly for Kerr nonlinear photonics, such as microresonator soliton frequency combs ("soliton microcombs"), chip-based supercontinua, and ultrathreshold optical parametric oscillators.

Multi-mode waveguides with tight optical confinement are widely used in integrated nonlinear photonics. The large waveguide cross-sections reduce optical loss by reducing light interaction with waveguide surface roughness. Indeed, state-of-the-art integrated waveguides of losses near 1 dB m$^{-1}$ are all multimode. In addition, stimulated Brillouin scattering and indirect-interband transition among different spatial modes are the basis of nonlinear adiabatic bends. Here, we optimize racetrack microresonators by replacing the two circular bends with two Euler bends, which have adiabatic radius transition from infinite (in the straight section) to finite (in the bending section). An Euler bend has a curvature (the inverse of path length) that varies linearly with its path length. Adiabatic bends, including Euler bends, have applications in railroad and highway engineering, and have later been used in integrated photonics. For example, a general design for adiabatic waveguide connection has been applied to create ultralow-loss, meter-long, suspended silica photonic delay lines. Modified Euler bends have been applied on multi-mode silicon-on-insulator (SOI) racetrack microresonators to achieve high $Q$. Nonlinear adiabatic bends have been used on Si$_3$N$_4$ microresonators to achieve low loss and broadband external coupling with bus waveguides. Euler bends have also been used in a tightly coiled, multi-mode waveguide resonator of 7.6 GHz FSR for stimulated Brillouin scattering in As$_2$S$_3$ glass.

Figure 1 highlights the difference between circular bends and adiabatic Euler bends. In Cartesian coordinate system $x - y$, the circular bend can be expressed as $x^2 + y^2 = R^2$, where $R$ is the constant bending radius. In comparison, the Euler bend, illustrated in Ref. 61, can be expressed as

$$\begin{align*}
x(s) &= \int_0^s \cos \left( \frac{\alpha}{2} u^2 \right) du \\
y(s) &= \int_0^s \sin \left( \frac{\alpha}{2} u^2 \right) du
\end{align*}$$

(1)

where $\alpha$ is the linear rate of curvature ($k$) change with path length ($s$), i.e. $k(s) = \alpha \cdot s$. The curvature $k$ determines the local bending radius, i.e. $R(s) = \left[ d\theta(s)/ds \right]^{-1} = k(s)^{-1}$.

To connect two straight waveguides separated by distance $d$ in the racetrack microresonator, a $\pi$-bend (i.e. 180° bend) consisting of two Euler bend sections and a circular bend section can be used, as illustrated in Fig. 1(a). The two Euler bend sections connect each straight waveguide to the circular bend of angle $\theta \in (0, \pi)$, allowing for adiabatic mode conversion from infinite radius ($R = \infty$) to a finite value $R_p = \left( \pi r_p \right)^{-1/2}$, and vice versa. Here, the Euler portion factor $p$, denoting the ratio of two Euler
bends in the total $\pi$-bend, is defined as

$$ p = 1 - \frac{\theta}{\pi} \quad (2) $$

We emphasize that, when the values of $p$ and $d$ are given, the linear curvature changing rate $\alpha$ is uniquely determined, as

$$ \alpha = \frac{2\sqrt{2} \int_0^{\sqrt{p}/\pi} \sin^2 t \, dt + \frac{2}{\sqrt{p}} \sin \frac{\pi(1-p)}{2}}{d^2} \quad (3) $$

Supplementary Information Note 1 shows the derivation and numerical plot of $\alpha$ as a function of $d$ and $p$. Particularly, the numerical plot of $\alpha$ as a function of $p$ with a constant $d$ shows that, the value of $\alpha$ decreases monotonously with $p$, and its minimum value is reached when $p = 1$. This may suggest that $p = 1$ gives the highest adiabaticity, as the linear rate $\alpha$ of bending curvature change is the smallest.

Figure 1(a) illustrates the difference between a full Euler bend ($\theta = 0, p = 1$), a partial Euler bend ($p \in (0, 1)$), and a circular bend ($\theta = \pi, p = 0$). To illustrate adiabatic mode conversion, finite-difference time-domain (FDTD) numerical simulations of mode propagation are performed (see Methods). In each case, the TE$_{00}$ mode of the straight waveguide is launched and propagates through the $\pi$-bend. Mode mixing during propagation is revealed by comparing the input and output modes, as well as the overall mode propagation profiles. It is observed that the launched TE$_{00}$ mode is preserved in the Euler bend ($p = 1$), while it experiences distortion in the partial Euler bend ($p = 0.6$) and circular bend ($p = 0$). The color bar denotes the field intensity in linear scale. Figure 1(b) shows optical microscope images showing fabricated Si$_3$N$_4$ racetrack microresonators with Euler bends ($p = 1$) and circular bends ($p = 0$). Both racetrack microresonators have the same span of $d = 60$ $\mu$m for the $\pi$-bends, and length of $L = 3500$ $\mu$m. The device footprint is approximately 0.21 mm$^2$. 

**Fig. 1 Schematics, designs and simulations of Euler bends for integrated Si$_3$N$_4$ racetrack microresonators.** a Illustration of the difference between Euler bends (blue) and circular bends (red) in Cartesian coordinate system $x - y$, to connect two straight waveguides (brown) in the racetrack microresonator within a $\pi$-bend ($180^\circ$ bend). The Euler portion factor $p$, which depends on the circular angle $\theta$, denotes the ratio of Euler bends (blue) in the total $\pi$-bend. Here, $p = 1$ ($\theta = 0$), $1 > p > 0$ ($\theta > 0$), and $p = 0$ ($\theta = \pi$) corresponds to Euler bend, partial Euler bend, and circular Euler bend, respectively. b Finite-difference time-domain (FDTD) simulations of mode propagation in three different bends, showing that higher $p$ offers better adiabatic mode conversion. In each case, the TE$_{00}$ mode of the straight waveguide is launched and propagates through the $\pi$-bend. Mode mixing during propagation is revealed by comparing the input and output modes, as well as the overall mode propagation profiles. It is observed that the launched TE$_{00}$ mode is preserved in the Euler bend ($p = 1$), while it experiences distortion in the partial Euler bend ($p = 0.6$) and circular bend ($p = 0$). The color bar denotes the field intensity in linear scale. c Optical microscope images showing fabricated Si$_3$N$_4$ racetrack microresonators with Euler bends ($p = 1$) and circular bends ($p = 0$). Both racetrack microresonators have the same span of $d = 60$ $\mu$m for the $\pi$-bends, and length of $L = 3500$ $\mu$m. The device footprint is approximately 0.21 mm$^2$. 

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Quantitative characterization of microresonator loss. Next, we experimentally study and compare racetrack microresonators with three different bends. We fabricated Si$_3$N$_4$ racetrack microresonators using the photonic Damascene reflow process (see Methods). Three different types of racetrack microresonators are fabricated, which have Euler bends ($p = 1$), partial Euler bends ($p = 0.6$) and circular bends ($p = 0$), as shown in Fig. 1. We emphasize that, these three racetrack microresonators are fabricated on the same photonic chip of $5 \times 5 \text{ mm}^2$, and are separated by $400 \mu\text{m}$ in a row (see design layout in Supplementary Information, Note 3). This is to minimize fabrication impact on device performance due to the parameter variation over the 4-inch wafer scale. The Si$_3$N$_4$ waveguide has a cross-section of $2.2 \mu\text{m}$ width and $0.90 \mu\text{m}$ height. All racetrack microresonators have the same span of $d = 60 \mu\text{m}$ for the $\pi$-bends, and length of $L = 3500 \mu\text{m}$ for the straight waveguides, to minimize the device footprint ($0.21 \text{ mm}^2$). The $60 \mu\text{m}$ span used in our Si$_3$N$_4$ platform is same as that used in high-Q SOI racetrack microresonators, despite that SOI waveguides have higher mode confinement. Figure 1(c) shows the microscope images and aspect ratios of racetrack microresonators with Euler bends ($p = 1$) or circular bends ($p = 0$).

To characterize the resonance linewidths (i.e. microresonator loss) and microresonator dispersion, we use frequency-comb-assisted, cascaded diode laser spectroscopy, to cover the entire telecommunication E- to L-band (1350 to 1630 nm). When light is coupled into the microresonator and the laser frequency scans continuously, the optical transmission spectrum of the microresonator is acquired (see Supplementary Information, Note 2). The instantaneous laser frequency of each recorded data point is calibrated by beating the laser with a commercial, self-referenced, fiber-laser-based optical frequency comb. The microresonator transmission spectrum is further referenced to a molecular absorption spectroscopy to extract the absolute laser frequency offset. This method allows to identify each resonance and obtain the precise resonance frequency $\omega/2\pi$. By fitting each resonance profile, the intrinsic loss $\kappa_0/2\pi$, bus-waveguide-to-microresonator external coupling strength $\kappa_{ex}/2\pi$, and loaded (total) linewidth $\kappa/2\pi = (\kappa_0 + \kappa_{ex})/2\pi$ are extracted for each resonance. Here we mainly focus on the T$_{E00}$ mode, and investigate mode interaction of the T$_{E00}$ mode with other spatial modes. First, we study the intrinsic loss $\kappa_0/2\pi$ and external coupling strength $\kappa_{ex}/2\pi$ of each resonance from the three different racetrack microresonators. Figure 2(a, c, e) reveal the wavelength dependence of $\kappa_0/2\pi$ and $\kappa_{ex}/2\pi$. Figure 2(b, d, f) plot the histogram of measured $\kappa_0/2\pi$ values from Fig. 2(a, c, e), respectively. For the racetrack microresonator with Euler bends ($p = 1$) shown in Fig. 2(a, b), no prominent wavelength dependence of $\kappa_0/2\pi$ is observed, and the most probable value in the histogram is $\kappa_0/2\pi = 15.5 \text{ MHz}$, corresponding to $2.4 \text{ dB m}^{-1}$ linear loss and a microresonator intrinsic quality factor $Q_0 = 13 \times 10^6$. However, for the racetrack microresonator with partial Euler bends ($p = 0.6$) shown in Fig. 2(c), higher $\kappa_0/2\pi$ with longer wavelength is observed, as well as spectrally periodic, vertical striations caused by inter-modal interference (see Supplementary Information, Note 2). The most probable value of $\kappa_0/2\pi$ is increased to 34.5 MHz as shown in Fig. 2(d). Both observations are due to the interaction of the T$_{E00}$ mode with other spatial modes. Since the eigenmode mismatch between the straight waveguide and the circular bend is larger for longer wavelength, the spatial mode interaction is stronger and causes higher loss. These two observations are further verified in the racetrack microresonator with circular bends ($p = 0$) shown in Fig. 2(e, f). Here, spatial mode interaction is so strong that many resonances experience greatly increased $\kappa_0/2\pi$, much higher than $\kappa_{ex}/2\pi$. Therefore, these resonances are strongly under-coupled and cannot be resolved in the transmission spectrum (see Supplementary Information, Note 2).

Quantitative characterization of microresonator dispersion and spatial mode interaction. To quantitatively characterize the strength of spatial mode interaction, we further study the microresonator dispersion profile, and investigate AMXs. Figure 3(a, e, i) show the measured integrated microresonator dispersion fitted with

$$D_{\text{int}}(\mu) = \omega_\mu - \omega_0 - D_\mu$$

$$D_{\text{int}} = D_\mu^2/2 + D_\mu^4/6 + D_4 \mu^4/24$$

where $\omega_\mu/2\pi$ is the $\mu$-th resonance frequency relative to the reference resonance frequency $\omega_0/2\pi$ (wavelength $\lambda_0$). $D_\mu/2\pi$ corresponds to microresonator FSR, $D_4/2\pi$ is GVD, and $D_2$ and $D_3$ are higher-order dispersion terms. To reveal AMXs, $D_2$ and $D_4$ are removed from $D_{\text{int}}$. Figure 3(b, f, j) and (c, g, k) show, respectively,

$$D_{\text{int}} - D_2 \mu^2/2 = D_4 \mu^4/6 + D_4 \mu^4/24$$

$$D_{\text{int}} - D_2 \mu^2/2 = D_4 \mu^4/6 + D_4 \mu^4/24$$

For the racetrack microresonator with Euler bends ($p = 1$), AMXs are only revealed when $D_2$ and $D_4$ terms are both removed. The histogram of resonance frequency deviations from the $D_4 \mu^4/24$ curve is plotted in Fig. 3(d), with the 90% confidence interval below 25 MHz, i.e. 90% of the total analyzed resonances have frequency deviations below 25 MHz. This value is on par with the total photon loss rate (i.e. $\kappa_0 + \kappa_{ex}/2\pi$) shown in Fig. 2(a). The residual AMXs revealed in Fig. 3(c) might also originate from the bus waveguide coupling section which has been revealed in FDTD simulations in Ref. 54. The bus waveguide coupling section can be optimized using asymmetric directional couplers.

In comparison, for the racetrack microresonator with partial Euler bends ($p = 0.6$), AMXs are already revealed when $D_2$ and $D_4$ terms are both removed. The enhanced AMXs lead to inaccurate $\kappa_0/2\pi$ extraction of Fig. 3(c) might also originate from the bus waveguide coupling section which has been revealed in FDTD simulations in Ref. 54. The bus waveguide coupling section can be optimized using asymmetric directional couplers.

Furthermore, for the racetrack microresonator with partial Euler bends ($p = 0$), the missing resonances and exaggerated AMXs prohibit to fit $D_{\text{int}}$ in Fig. 3(i), leading to infeasibility to extract $D_2$ and $D_4$ values. Many resonances have frequency deviations more than 1 GHz, as shown in Fig. 3(l). We emphasize that, such exaggerated AMXs are caused by the circular bends of only 60 $\mu\text{m}$ diameter for 19.8 GHz FSR. The previous work has shown single soliton generation in racetrack microresonators driven by picosecond optical pulses. However, there, the diameter of the
circular bend is 400 μm for 28 GHz FSR and 0.6 mm² device footprint (see design layout in Supplementary Information, Note 3), thus the eigenmode mismatch between the straight waveguide and the circular bend is much smaller than that in our current case, leading to weaker mode coupling.

Single soliton generation and K-band phase noise characterization. Finally, we demonstrate single soliton generation of 19.8 GHz repetition rate in the racetrack microresonator with Euler bends (p = 1). When the continuous-wave (CW) pump laser scans across the resonance from the blue-detuned side to the red-detuned side, a step indicating soliton formation in the microresonator transmission spectrum is observed. Here we observe a soliton step length of ~0.5 ms, on par with the previous studies where operation at the quiet point enables more than 20 dBc/Hz phase noise reduction, here we only observe less than 4 dBc/Hz reduction measured within 1 kHz to 100 kHz Fourier offset frequency. To evidence the phase noise reduction at the “quiet point”, the soliton repetition rate shift and the phase noise value at 3.852 kHz Fourier offset frequency where the diode laser (Toptica CTL) exhibits a characteristic phase noise feature, are measured with different detuning values, as shown in Fig. 4(c). It seems that the minimum phase noise is reached at 217.2 MHz detuning. The weak quiet point effect agrees with the soliton spectrum for which dispersive wave generation is inhibited, due to the suppressed spatial mode interaction and avoided-mode crossings.

Previously, on integrated Si₃N₄ platform, single solitons of repetition rates below 20 GHz driven by CW pump have only been generated in microring resonators. The microring resonator of 19.6 GHz FSR has a footprint of 4.2 mm², 20 times larger than our racetrack microresonator of 19.8 GHz FSR (0.21 mm²). Such vast difference in device footprint is highlighted by the large capacitance of piezoelectric modulators is proportional to the device area. In addition, the large aspect ratio of the racetrack, length over a broad wavelength range for each sample. The data shown in (b, d, f) are histogram of κ/2π for (a, c, e) for each sample.

Fig. 2 Resonance linewidth characterization of racetrack microresonators with different bends. Racetrack microresonators with Euler bends (Euler portion p = 1) (a, b), partial Euler bends (p = 0.6) (c, d), and circular bends (p = 0) (e, f) are experimentally characterized. The data shown in (a, c, e) are measured intrinsic linewidth κ/2π and external coupling rate κappa/2π over a broad wavelength range for each sample. The data shown in (b, d, f) are histogram of κ/2π from (a, c, e) for each sample.
size limits the device shape and aspect ratio. Finger- or snail-shaped microresonators have been developed10,79 to confine the microresonator in one or few EBL writing fields, such that the impact of stitching errors is minimized15,80. For example, we note that, very recently, Ref.79 has shown 1 mm² device footprint for microresonators of 14.0 and 20.5 GHz FSR, and single soliton generation in these devices.

Conclusion
In summary, we adapt60,61, optimize, and implement Euler bends to build compact racetrack microresonators based on ultralow-loss, multimode, Si3N4 photonic circuits. The optimized racetrack microresonator has a significantly reduced device footprint, critical for high device density and integration81. It can serve as building blocks for nonlinear photonic applications, such as microwave-repetition-rate soliton microcombs52,82, travelling-wave optical parametric amplifiers15,83,84, frequency conversion85, or resonant electro-optic modulators86,87 and frequency combs55. The adiabatic Euler bend is also useful for linear circuits based on beam splitters and interferometers that are widely used in integrated programmable processors88 and photonic quantum computing89,90.

The simple design rules and algorithms illustrated here can be easily implemented in Si3N4 foundry process8.

Methods
Finite-difference time-domain simulations. In the FDTD simulations shown in Fig. 1, the fundamental TE00 mode source at 1550 nm wavelength is launched at the input ports of the three π − bends of d = 60 μm. The normalized transmission at the output ports are evaluated in each case. A perfectly matched layer (PML) boundary is used in the simulations. In addition, TE00 mode couplings to other higher-order modes are examined by expanding the transmitted optical field using a mode expansion monitor (a build-in function provided by Lumerical FDTD). The normalized power transmission and power distribution in few eigenmodes are listed in Table 1. The transmitted power in the TE00 mode features more than 99.96% power in the full Euler bend (p = 1), which is higher than the values in the partial Euler bend (87.15% for p = 0.6) and in the circular bend (82.19% for p = 0).

Sample fabrication. The Si3N4 integrated devices are fabricated using the photonic Damascene process11. Waveguide patterns, as well as filler patterns to release the tensile film stress of Si3N4, are exposed with a KrF (248 nm) deep-ultraviolet (DUV) stepper lithography. The patterns are then transferred from the photoresist mask to the thermal wet SiO2 substrate using dry etching, to create waveguide preforms. A thermal reflow step, where the wafer is annealed at 1250°C, is performed to reduce the sidewall roughness of waveguide preforms. A Si3N4 film of thickness more than 1000 nm is then deposited on the patterned wafer via low-
avoided-mode crossings. The absence of a strong quiet point is due to the inhibited dispersive wave generation that is caused by the suppressed spatial mode interaction and excess Si3N4 and planarize the wafer top surface. Finally, top SiO2 cladding is deposited on the wafer, followed by high-temperature annealing. The entire wafer is then separated into chips for experiments.

Data availability

The data that support the plots within this manuscript and other findings of this study are available on Zenodo (https://doi.org/10.5281/zenodo.5845121). All other data used in this study are available from the corresponding authors upon reasonable request.

Table 1 FDTD simulation results for transmitted power distribution in selected waveguide eigenmodes, for d = 60 µm circular bend (p = 0), partial Euler bend (p = 0.6) and Euler bend (p = 1). The optical field distributions in these three bends are shown in Fig. 1.

| Mode power | Circular bend (p = 0) | Partial Euler bend (p = 0.6) | Euler bend (p = 1) |
|------------|-----------------------|-----------------------------|-------------------|
| Total power | 0.9993                | 0.9997                      | 0.9999            |
| TE00 power | 0.8219                | 0.8715                      | 0.9996            |
| TE10 power | 0.1697                | 0.1247                      | 1.95e-4           |
| TE20 power | 0.0073                | 0.0035                      | 1.2e-05           |

pressure chemical vapour deposition (LPCVD), filling the trenches and forming the waveguides. Chemical-mechanical polishing (CMP) is then used to remove the excess Si3N4 and planarize the wafer top surface. Finally, top SiO2 cladding is deposited on the wafer, followed by high-temperature annealing. The entire wafer is then separated into chips for experiments.

Fig. 4 Single soliton generation in the racetrack microresonator with Euler bends, and the phase noise characterization of soliton repetition rate. a Single soliton spectra of 19.8 GHz repetition rate. No prominent dispersive wave features caused by avoided-mode crossings (AMXs) are observed. The single soliton spectrum fit shows a 3-dB bandwidth of 16.3 nm, corresponding to a pulse duration of 156 fs. The estimated on-chip continuous-wave (CW) pump power is 55.7 mW. Note that a band-pass filter is used to filter out the EDFA’s amplified spontaneous emission noise in the pump laser, and a fiber Bragg grating is used to filter out the pump laser in the soliton spectra. Inset: When the pump laser scans across the resonance, a soliton step of ~0.5 ms length in the microresonator transmission is seen (marked in the gray zoom). b Single-sideband (SSB) phase noise measurement with different soliton detuning values. No prominent phase noise change due to a quiet point operation is observed. The feature at 3.852 kHz Fourier offset frequency is caused by the diode laser pump. c SSB phase noise at 3.852 kHz Fourier offset frequency and measured repetition rate shift with different soliton detuning values. The absence of a strong quiet point is due to the inhibited dispersive wave generation that is caused by the suppressed spatial mode interaction and avoided-mode crossings.

References

1. Rickman, A. The commercialization of silicon photonics. Nat. Photonics 8, 579–582 (2014).
2. Thomson, D. et al. Roadmap on silicon photonics. J. Opt. 18, 073003 (2016).
3. Agrell, E. et al. Roadmap of optical communications. J. Opt. 18, 063002 (2016).
4. Komljenovic, T. et al. Heterogeneous silicon photonic integrated circuits. J. Lightwave Technol. 34, 20–35 (2016).
5. Kaur, P. et al. Hybrid and heterogeneous photonic integration. APL Photonics 6, 061102 (2021).
6. Margalit, N. et al. Perspective on the future of silicon photonics and electronics. Appl. Phys. Lett. 118, 220501 (2021).
7. Moss, D. J., Morandotti, R., Gaeta, A. L. & Lipson, M. New CMOS-compatible platforms based on silicon nitride and hybrid for nonlinear optics. Nat. Photonics 7, 597 (2013).
8. Muñoz, P. et al. Foundry developments toward silicon nitride photonics from the mid-infrared to the mid-infrared. IEEE J. Sel. Top. Quantum Electron. 25, 1–13 (2019).
9. Henry, C. H., Kazarian, R. F., Lee, H. J., Orlowski, K. J. & Katz, L. E. Low loss Si3N4-SiO2 optical waveguides on Si. Opt. Lett. 26, 2621–2624 (1987).
10. Xuan, Y. et al. High-Q silicon nitride microresonators exhibiting low-power frequency comb initiation. Optica 3, 1171–1180 (2016).
11. Liu, J. et al. High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits. Nat. Commun. 12, 2236 (2021).
12. Ji, X. et al. Exploiting ultralow loss multimode waveguides for broadband frequency combs. Laser Photonics Rev. 15, 2000353 (2021).

13. Yu, Z., Tawara, A., Andrekson, P. A. & Torres-Company, V. High-Q Si$_3$N$_4$ microresonators based on a subtractive processing for kerr nonlinear optics. Opt. Express 27, 35719–35727 (2019).

14. Okawachi, Y. et al. Bandwidth shaping of microresonator-based frequency combs via dispersion engineering. Opt. Lett. 39, 3535–3538 (2014).

15. Yang, Q.-F., Yi, X., Wang, C., Cheng, R., Shams-Ansari, A. & Lonker, M. Spatial-mode-interaction-induced dispersive waves and their active tuning in microresonators. Optica 3, 1132–1135 (2016).

16. Gyger, F. et al. Observation of stimulated brillouin scattering in silicon nitride microresonators. Phys. Rev. Lett. 124, 013902 (2020).

17. Gaeta, A. L., Lipson, M. & Kippenberg, T. J. Photonic-chip-based frequency combs. Nat. Photonics 13, 156–169 (2019).

18. Sohn, D. B., Kim, S. & Bahl, G. Time-reversal symmetry breaking with Brillouin microcombs. Nat. Photonics 14, 486–491 (2020).

19. Kippenberg, T. J., Gaeta, A. L., Lipson, M. & Gorodetsky, M. L. Dissipative Kerr solitons in optical microresonators. Nat. Commun. 10, 406–414 (2016).

20. Lu, X. et al. Efficient telecom-to-visible spectral translation through ultralow power nonlinear nanophotonic devices. Nat. Photonics 13, 593–601 (2019).

21. Zhang, M. et al. Ultrahigh-Q silicon racetrack resonators. Photon. Res. 8, 684–689 (2020).

22. Zhang, M., Wang, C., Cheng, R., Shams-Ansari, A. & Loncar, M. Monolithic ultra-high-Q lithium niobate microresonating oscillator. Optica 4, 1536–1537 (2017).

23. Eggleton, B. J., Poulton, C. G., Rakich, P. T., Steel, M. J. & Bahl, G. Brillouin integrated photonics. Nat. Photonics 13, 664–677 (2019).

24. Sohn, D. B. et al. Frequency comb assisted diode laser spectroscopy for measurement of kerr nonlinear optics. Nat. Photonics 13, 129391 (2014).

25. Liu, J. et al. Photonic microwave generation in a lithium niobate microresonating oscillator. Opt. Lett. 39, 1314–1316 (2014).

26. Yu, Z. & Fan, S. Complete optical isolation created by indirect interband photonics. Nat. Photonics 3, 91–94 (2009).

27. Lira, H., Yu, Z., Fan, S. & Lipson, M. Electrically driven nonreciprocity induced by interband photonic transition on a silicon chip. Phys. Rev. Lett. 109, 033901 (2012).

28. Kim, S. & Bahl, G. Time-reversal symmetry breaking with acoustic pumping of nanophotonic circuits. Nat. Photonics 12, 91–97 (2018).

29. Kittlaus, E. A., Otterstrom, N. T., Khare, P., Gerst, L., Rakich, S. & Rakich, P. T. Nonreciprocal interband brillouin modulation. Nat. Photonics 12, 613–619 (2018).

30. Tian, H. et al. Magnetic-free silicon nitride integrated optical isolator. Nat. Photonics 15, 828–836 (2021).

31. Levy, J. S., Foster, M. A., Gaeta, A. L. & Lipson, M. Harmonic generation in silicon nitride ring resonators. Opt. Express 19, 11415–11421 (2011).

32. Levy, J. et al. Mode-locked dark pulse kerr combs in normal-dispersion microresonators. Nat. Photonics 9, 594 (2015).

33. Matsko, A. B., Liang, W., Savchenkov, A. A., Efremov, D. & Maleki, L. Optical cherenkov radiation in overmoded microresonators. Opt. Lett. 41, 2907–2910 (2016).

34. Yang, Q.-F., Yi, X., Yang, K. & Vahala, K. Spatial-mode-interaction-induced dispersive waves and their active tuning in microresonators. Optica 3, 1132–1135 (2016).

35. Bao, C. et al. Spatial mode-interaction induced single soliton generation in microresonators. Optica 4, 1011–1015 (2017).
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Author contributions

X.J. and J.L. performed the numerical simulation and analytical study. X.J. and J.L. designed the samples, with the assistance from Z.Q., J.L. and R.N.W. fabricated the samples. X.J. and J.H. characterized the samples with assistance from J.R. and J.L. J.H. performed the soliton generation and phase noise measurement with the assistance from J.R., X.J. and J.L. X.J., J.L. and J.H. analyzed the data. J.L. and X.J. wrote the manuscript with input from others. T.J.K. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information

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Correspondence and requests for materials should be addressed to Junqiu Liu or Tobias J. Kippenberg.

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