Monolithic piezoelectric control of soliton microcombs

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High-speed actuation of laser frequency1 is critical in applications using lasers and frequency combs2,3, and is a prerequisite for phase locking, frequency stabilization and stability transfer among optical carriers. For example, high-bandwidth feedback control of frequency combs is used in optical-frequency synthesis4, frequency division5 and optical clocks6. Soliton microcombs7,8 have emerged as chip-scale frequency comb sources, and have been used in system-level demonstrations9,10. Yet integrated microcombs using thermal heaters have limited actuation bandwidths11,12 of up to 10 kilohertz. Consequently, megahertz-bandwidth actuation and locking of microcombs have only been achieved with off-chip bulk component modulators. Here we demonstrate high-speed soliton microcomb actuation using integrated piezoelectric components13. By monolithically integrating AlN actuators14 on ultralow-loss Si3N4 photonic circuits15, we demonstrate voltage-controlled soliton initiation, tuning and stabilization with megahertz bandwidth. The AlN actuators use 300 nanowatts of power and feature bidirectional tuning, high linearity and low hysteresis. They exhibit a flat actuation response up to 1 megahertz—that is, extendable to higher frequencies by overcoming coupling to acoustic contour modes of the chip. Via synchronous tuning of the laser and the microresonator, we exploit this ability to frequency-shift the optical comb spectrum (that is, to change the comb’s carrier-envelope offset frequency) and make excursions beyond the soliton existence range. This enables a massively parallel frequency-modulated engine16,17 for lidar (light detection and ranging), with increased frequency excursion, lower power and elimination of channel distortions resulting from the soliton Raman self-frequency shift. Moreover, by modulating at a rate matching the frequency of high-overtone bulk acoustic resonances18, resonant build-up of bulk acoustic energy allows a 14-fold reduction of the required driving voltage, making it compatible with CMOS (complementary metal–oxide–semiconductor) electronics. Our approach endows soliton microcombs with integrated, ultralow-power and fast actuation, expanding the repertoire of technological applications of microcombs.

In recent years there has been major progress in the development of soliton microcombs7, which are miniaturized, broadband, high-repetition-rate, coherent frequency combs. These soliton microcombs are generated in nonlinear optical microresonators driven by continuous-wave (CW) lasers, in which dissipative Kerr solitons are formed19,20. Importantly, recent advances in CMOS-compatible low-loss photonic integrated circuits have enabled the manufacture of chip-based microcombs8. Such microcombs could allow co-integration of multiple functionalities on a chip, as well as compact, low-power-consumption, electronically controlled frequency comb devices21,22 for field-deployable applications.

Silicon nitride (Si3N4)23 has emerged as a leading platform for integrated soliton microcombs8: several system-level applications based on Si3N4 have been demonstrated8, including coherent communication9, ultrafast ranging, parallel coherent lidars10, astronomical spectrometer calibration, optical frequency synthesizers10 and atomic clocks. For applications of laser frequency combs, the ability to achieve high-speed actuation of comb teeth, as well as the repetition rate, is critical1. For example, locking combs to microwave standards is key to optical frequency synthesis1. Phase-locking of combs to stable reference cavities is also central for low-noise microwave generation via optical frequency division1. Optical clocks require frequency combs

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Frequency components (with repetition rate $f_{\text{rep}}$) match the HBAR modes (with mode spacing $f_{\text{HBAR, FSR}}$). b. False-colour SEM image of the sample cross-section, showing Al (yellow), AlN (green), Mo (red), Si$_3$N$_4$ (blue) and the optical mode (rainbow). c. Optical micrograph showing the Si$_3$N$_4$ microresonator (red dashed line) with a disk-shape AlN actuator. d. Resonance shift versus applied voltage. The linear tuning coefficient at d.c. is $\delta V/V = 15.7$ MHz V$^{-1}$. A weak hysteresis is observed. e. $\delta V$ incr./decr., voltage increase / decrease; meas., measured data. e. Resonance shift for all TE$_{00}$ resonances in the wavelength range from 1,500 nm to 1,630 nm, when the applied voltage changes from $-100$ V to +150 V. The wavelength-dependent tuning results from a 3.3 MHz change in microresonator FSR.

**Device fabrication and characterization**

Figure 1a shows schematically the use of piezoelectric AlN to actuate the soliton microcomb, via either the stress-optic effect or high-overtone bulk acoustic resonator (HBAR) modes. The inset (boxed) shows the route to efficient and fast microcomb actuation by modulating the microresonator with Fourier frequency components matching the HBAR modes, which will be discussed later. The AlN actuators are monolithically integrated on ultralow-loss Si$_3$N$_4$ waveguides fabricated using the photonic Damascene reflow process. In order to preserve the ultralow waveguide loss of 2 dB m$^{-1}$, a 2.4-μm-thick SiO$_2$ top cladding is deposited on the Si$_3$N$_4$ waveguides, before the piezoelectric actuators are deposited and patterned. The piezoelectric actuators are made from polycrystalline AlN as the main piezoelectric material, using molybdenum (Mo) as the bottom electrode (ground) and substrate to grow polycrystalline AlN, and aluminium (Al) as the top electrode. Figure 1b, c shows respectively a scanning electron microscopy (SEM) image of the sample cross-section, and a top-view optical micrograph (original, unprocessed micrographs are shown in Extended Data Figs. 6 and 7).

We first characterize the stress-optic tuning of the microresonator TE$_{00}$ resonances in the fundamental transverse-electric mode (TE$_{00}$).
Voltage-controlled soliton microcombs

We next demonstrate piezoelectric soliton initiation, switching and bandwidth tuning. A CW laser is coupled into the microresonator. By varying the voltage applied to the AlN actuator, the soliton is initiated by tuning the resonance to the laser using a setup shown in Fig. 2a. The laser is initially blue-detuned by 1 GHz from a microresonator resonance, and launches 15 mW of power into the waveguide (with a 60% coupling efficiency per facet chip). A typical soliton step of millisecond length is shown in Fig. 2b. Though not required for soliton initiation, we monitor the resonance–laser detuning using an electro-optic modulator (EOM) and a vector network analyser (VNA). As shown in Fig. 2c, left, the resonance is initially tuned to the laser (0 + 81 V), and subsequently generates modulation instability (MI, 81 V) and a multi-soliton state (MS, 85 V). Next, the AlN voltage is reduced such that the backward tuning enables switching to the single soliton state (SS, 79 V). The soliton detuning, as well as the bandwidth, is further increased by increasing the voltage (90 V). S-res., soliton resonance; C-res., cavity resonance. In Fig. 2d, the measured soliton states with different applied voltages. The voltage-controlled AlN actuator can be used to implement feedback and to eliminate detuning drift for long-term soliton stabilization (see Methods).

**High-speed soliton actuation and locking**

Next we show that the AlN actuator allows microresonator modulation that can be used to manipulate the soliton repetition rate. Figure 3a shows the experimental set-up used to characterize the frequency response $S_0(\omega)$ of the AlN actuator when transducing electrical to optical modulation (with $\omega$ being the modulation frequency). As shown in Fig. 3d, the measured $S_0(\omega)$ has multiple peaks starting from 200 kHz, which correspond to different mechanical modes of the microcomb excited by the AlN actuator. The mechanical modes with frequencies from 246 kHz to about 17 MHz are contour modes of the entire chip. Figure 3b shows the measured contour modes around 246 kHz, using finite-element modelling based on the actual chip size of 4.96 mm × 4.96 mm. These contour modes only exist with free boundary conditions. The broad peak at 17 MHz shown in Fig. 3d is the fundamental HBAR mode, confined vertically over the chip thickness and the material stack (8.4 µm SiO$_2$ and 213 µm Si). The resonances at multiples of 17 MHz are higher-order HBAR modes. Although narrow-band, HBAR modes offer new features, such as transducing a modulation to derive an error signal via the Pound–Drever–Hall (PDH) technique. Figure 3c compares the PDH error signals generated when applying 82.44 MHz and 91.71 MHz modulation frequencies directly to the AlN actuator (see Methods). Since 91.71 MHz corresponds to an HBAR mode, the error signal is ten times stronger compared to the other frequency, as marked in Fig. 3d. More error signals at other frequencies are shown in Methods and Extended Data Fig. 4.

The relatively flat $S_0(\omega)$ response up to approximately 800 kHz allows soliton repetition rate stabilization via AlN actuation. As the soliton repetition rate, $\nu_{rep}$ = 191.0 GHz, is not directly measurable, we use an electro-optic frequency comb (EO comb) of 14.6974 GHz line spacing, and measure and the beat signal between line number (no.) –1 of the EO comb, as illustrated in Fig. 3e. Both microcomb and EO comb are generated with the same pump laser.
The measured beat signal is further compared to a reference signal of 60.0 MHz, and the error signal is fed-back to the AlN actuator, such that the actuation on the microresonator stabilizes the soliton repetition rate to the EO comb line spacing (see Methods). Figure 3f, g compares the measured beat signal between line no. −1 of the microcomb and line no. −13 of the EO comb (Fig. 3f), and the phase noise of the beat signal in the cases of free-running and locked states (Fig. 3g), in comparison with the phase noise of the 60.0 MHz reference signal (Fig. 3g). The locking bandwidth, determined by the merging point of the two phase noise curves (red and blue), is 0.6 MHz. This bandwidth is wide for piezoelectric optical frequency actuators, compared to conventional lasers where the piezo response is typically limited to a few kilohertz (similar to integrated heaters). In addition, the 0.6 MHz bandwidth is limited by the chip contour modes of our sample. By engineering the contour modes in smaller chips, this bandwidth could be extended to several megahertz.

**Soliton-based parallel lidar engine**

We further show that the AlN actuator can be a key component in a soliton-based, massively parallel, frequency-modulated continuous-wave (FMCW) lidar. The previously demonstrated scheme relied on scanning the pump laser’s frequency $v_\text{P}$ over the soliton existence range $\Delta v_\text{s} = v_\text{L} - v_\text{P}$, that is, $v_\text{L} - v_\text{P} \in [v_\text{c}, v_\text{L}]$, with $v_\text{L}$ being the optical resonance frequency, and $v_\text{c}$ and $v_\text{L}$ being the boundaries of the soliton existence detuning range. This results in the transfer of a frequency chirp to all soliton comb teeth, as shown in Fig. 4a. Combined with diffractive optics that disperses multiple frequency lines, this approach to FMCW lidar allows high-speed parallel acquisition of both velocity and position in each channel. However, varying the soliton detuning has three limitations. First, this leads to variation in the soliton spectral bandwidth and power, which limits the number of usable optical channels. Second, the Raman self-frequency shift induces variation in soliton repetition rate (that is, comb line spacing) as the detuning varies, leading to unequal chirp of the comb teeth and chirp distortions. Third, gigahertz frequency excursion of the pump laser ($\Delta v_\text{P}$) requires a gigahertz-wide soliton existence range ($\Delta v_\text{s}$), necessitating operation at a high pump power of several watts.

These limitations can be overcome by using AlN actuation of the microresonator, such that the microresonator resonance $v_\text{c}$ is modulated synchronously with the pump frequency $v_\text{P}$, in order to maintain a constant soliton detuning, $v_\text{L} - v_\text{c}$. We experimentally investigated both schemes, that is, (1) scanning the pump laser within the soliton existence range, and (2) synchronously modulating the pump laser and the microresonator resonance (‘feed-forward’), as shown in Fig. 4b, c, respectively. For the feed-forward scheme, a triangular signal of frequency $f_\text{mod}$ and peak-to-peak voltage $U_{\text{pp}}$ is applied to both the pump laser and the AlN actuator. A phase shifter, an attenuator and a high-voltage amplifier (HVA) are used to modify the triangular signals in order to synchronize the resonance tuning to the laser tuning and to achieve the same frequency excursions (see Methods). Figure 4b–d illustrates the differences in soliton spectrum and integrated soliton pulse power using both schemes, and highlights the advantages of the feed-forward scheme. First, the pump frequency chirp $\Delta v_\text{P}$ can be substantially larger than the soliton existence range $\Delta v_\text{s}$, simultaneously allowing soliton operation with tens of milliwatts of power, compatible with state-of-the-art integrated lasers. Second, the soliton spectrum and the repetition rate are nearly constant and are not affected by the pump frequency chirp.

Figure 4e compares the frequency excursions of different soliton comb lines. When the soliton detuning is scanned at frequency $f_\text{mod} = 10$ kHz (blue, solid line), a frequency-excitation dependence of the comb line number is found, resulting from the soliton repetition.
Fig. 4 | Hybrid AlN-Si₃N₄ soliton lidar engine. a, Schematic of soliton-based parallel FMCW lidar. A chirped pump (ν₂) transduces synchronous modulation to all comb lines (for example, ν₂ and ν₂'), with the same modulation rate and frequency excursion (ν₁ = ν₂ = ν₁'). These comb lines are spatially dispersed with diffractive optics (such as a prism), and illuminate static or moving objects (for example, the tree and the car), which allows the realization of parallel ranging. b, Top panel, the lidar scheme employing a soliton detuning scan, with the pump centred at ν₁ chirping within the soliton existence range (green shaded), and the fixed microresonator resonance ν₁'. The varying soliton detuning Δν induces the soliton spectrum variation, as shown in the bottom panel. In this scheme, the pump frequency excursion can substantially exceed the soliton existence range (green shaded). c, Comparison of the frequency excursions of different soliton comb lines, using different approaches including: a soliton detuning scan at a rate of 10 kHz (blue dots), a feed-forward scan at a rate of 10 kHz with an applied voltage of 125 V (red dots), a feed-forward scan at a rate of 18.308 kHz with an applied voltage of 7.5 V (red stars), and a feed-forward scan at a rate of 18.322 kHz with an applied voltage of 7.5 V (red diamonds).

In summary, we demonstrate piezoelectric control of soliton micromodes by applying modulation with f_mod = 18.308 MHz, coinciding with the fundamental HBAR mode and a contour mode, we impart a 1.6 GHz pump frequency excursion with a voltage applied to the AlN of only U_pp = 7.5 V. This modulation corresponds to an equivalent tuning speed of 58.6 MHz s⁻¹. The corresponding a.c. resonance tuning coefficient is δν/δV = 219 MHz V⁻¹, which is 14 times larger than the d.c. tuning value of δν/δV = 15.7 MHz V⁻¹. Applying modulation with f_mod = 18.322 MHz, while still coinciding with the fundamental HBAR mode but not a contour mode, the tuning coefficient is reduced to δν/δV = 133 MHz V⁻¹.

In summary, we demonstrate piezoelectric control of soliton microcomb, by monolithically integrating AlN actuators on ultralow-loss Si₃N₄ waveguides. We show voltage-controlled soliton initiation, tuning and megahertz-bandwidth locking. By engineering the contour modes
of the chip, the actuation bandwidth could be further increased. This novel approach to microcomb actuation not only benefits existing applications, but also allows synchronous scanning of the pump laser and microresonator, as required to build parallel FMCW lidar engines. The unprecedented bandwidth and low crosstalk offered by these piezoelectric actuators enable the suppression of parasitic line power fluctuations and Raman self-frequency shifts for lidar applications.

Moreover, by modulating the microcomb at the HBAR frequency, the resonant build-up of bulk acoustic energy allows a 14-fold reduction of the required driving voltage. While polycrystalline AlN is used in our current work, with scandium-doped AlN (ref. 47) the operation voltage can be reduced by more than two times to a CMOS voltage range. By future co-integration of CMOS microelectronic circuitry on a close-by-die, compactly packaged microcombs with rapid electronic actuation are attainable.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2465-8.

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Methods

Characterization of resonance tuning
The experimental set-up used to characterize the resonance frequency as a function of the voltage applied to the AlN actuator is shown in Extended Data Fig. 1a. A tunable laser (Toptica CTL) is locked to a Si₃N₄ microresonator resonance, via a PDH lock loop using an EOM to apply phase modulation to the laser light. When the resonance is tuned by varying the applied voltage, the laser frequency follows the resonance shift. The beat signal between the laser locked to the resonance and a reference laser (another Toptica CTL) is measured using a fast photodiode and an electrical spectrum analyser (ESA). A programmable d.c. power supply (Keithley 2400) is used to apply the voltage to the AlN actuator. A ramp signal is applied to the power supply which outputs a voltage between ±140 V with a ramp voltage increment/decrement of 2.8 V. The interval time between two subsequent measurements is 200 ms. The change in the two lasers’ beatnote signal recorded by the ESA corresponds to the resonance frequency shift, as one laser is locked to the resonance and the other is frequency-fixed. These measurements are repeated continuously for multiple (3 to 5) scans between ±140 V in order to confirm the hysteresis. Extended Data Fig. 1b shows two consecutive sweeps between ±100 V. The standard deviation of frequency at each voltage value is evaluated using the measured frequencies with respect to the fitted frequency on the linear curve. The error bars are added in Extended Data Fig. 1b (the error segments correspond to twice the standard deviation). It can be seen that the measurement uncertainty is smaller than the observed hysteresis. Overall, we estimate that our measurement uncertainty is below 15 MHz.

Microresonator Q and dispersion
Extended Data Figure 2a compares the measured loaded linewidths with different applied voltages. The resonances remain critically coupled, and no linewidth change is observed. The estimated intrinsic quality factor, Qᵢ > 15 × 10⁶, with integrated AlN actuators is identical to bare microresonators without AlN. Extended Data Fig. 2b compares the microresonator dispersion of the TE₀₀ mode with different applied voltages. The microresonator dispersion is defined as $D_\text{m}(\mu) = \omega_\mu - \omega_0 - D_0 \mu = D_0 \mu^2 / 2 + D_2 \mu^4 / 6 + ...$, where $\omega_\mu / 2\pi$ is the frequency of the $\mu$th resonance relative to the pump resonance $\omega_0 / 2\pi$. $D_0 / 2\pi$ corresponds to the microresonator FSR, $D_2 / 2\pi$ is the group velocity dispersion (GVD) and $D_4 / 2\pi$ is the third-order dispersion. At the pump wavelength of 1,550.0 nm, with $\pm 100$ V bias, the fitted $D_2 / 2\pi = 191.0118$ GHz and $D_4 / 2\pi = 3.404$ MHz; with $\pm 100$ V bias, the fitted $D_2 / 2\pi = 191.0065$ GHz and $D_4 / 2\pi = 3.422$ MHz. Therefore, the microresonator FSR change is $\Delta D_2 / 2\pi = 5.3$ MHz, and the GVD change is $\Delta D_4 / 2\pi = 18$ kHz.

Long-term soliton stabilization
The experimental set-up for soliton stabilization over 5 h is shown in Extended Data Fig. 3a. A feedback loop is applied to fix the soliton detuning at 317 MHz and eliminate the detuning fluctuation over the long term. The VNA is used only to monitor the soliton detuning. Extended Data Fig. 3b shows the evolution of three comb lines over 5 h. The final soliton loss after 5 h is caused by the drift of the fibre–chip coupling using suspended lensed fibres, and can be mitigated by gluing the fibres to the chip.

Generation of PDH error signals
Extended Data Figure 4a shows the experimental set-up used to generate PDH error signals using HBAR modes induced by the AlN actuation. The measured $S_2(\omega)$ response of the AlN actuation, up to 400 MHz, is plotted on the linear frequency scale in Extended Data Fig. 4b. When the laser is on-off-resonance, different modulation frequencies corresponding to different HBAR modes are investigated, which are marked with stars in Extended Data Fig. 4b. The PDH error signals modulated at these HBAR frequencies are shown in Extended Data Fig. 4c, as well as the studied microresonator resonances. A microwave source providing 8 dBm RF power is used to modulate the Si₃N₄ microresonator via AlN actuation, for all the HBAR frequencies.

Soliton source for parallel FMCW lidar
Extended Data Figure 5a shows the experimental set-up used to synchronously scan the microresonator and the pump laser (that is, the feed-forward scheme). A single-sideband modulator driven by a voltage-controlled oscillator (VCO) is used to fast-scan the laser frequency, instead of directly scanning the laser piezo, owing to the limited piezo scan speed of our laser (~200 Hz). A voltage ramp signal from the same dual-channel arbitrary waveform generator (AWG) is applied to the VCO and the AlN actuator. The ramp signal sent to the AlN actuator is further amplified by a high-voltage amplifier (HVA) with ±50 V amplification and a 3-dB bandwidth of ~5 MHz. The synchronous scan of the laser frequency and the microresonator resonance is performed by adjusting the amplitude and the phase of the ramp signal applied to the VCO. A PDH lock can further improve the synchronization by locking the resonance to the laser with a constant frequency detuning. Initially, the ramp signal from the AWG with a peak-to-peak voltage $U_{\text{pp}} = 3$ V (the HVA amplifies to 150 V) and a 10 kHz scanning rate is applied to the AlN. The amplitude $U_{\text{pp}}$ and the phase of the ramp signal driving the VCO are adjusted until a stable C-resonance is observed on the VNA. Tuning into soliton states is realized either by changing the laser frequency via laser piezo tuning, or by turning on and off the VCO, which allows fast tuning of the laser to the effectively red-detuned side of the resonance. A reference laser is used to probe the chirp of different comb lines (the pump line and ±10th comb lines, and so on). A fast oscilloscope of 2 GHz bandwidth and 5 × 10⁶ samples s⁻¹ is used to capture the heterodyne beatnote detected on the fast photodiode, for a short-time Fourier transformation and fitting to a triangular signal.

Data availability
The data that support the plots within this paper and other findings of this study are available on Zenodo (https://doi.org/10.5281/zenodo.3903724). All other data used in this study are available from the corresponding authors upon reasonable request.

Acknowledgements
We thank J. Riemensberger, A. Lukashchuk and M. Karpov for discussions. This work was supported by contract HR0001-15-C-055 (DOODS) from the Defense Advanced Research Projects Agency (DARPA), Microsystems Technology Office (MTO), by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF, under award no. FA9550-19-1-0250, and by the Swiss National Science Foundation under grant agreement no. 176563 (BRIDGEC). E.L. acknowledges support from the European Space Technology Centre under ESA contract no. 4000116145/16/NL/MH/GM. Samples were fabricated in the EPFL Center of

Kerr-microresonator frequency combs.

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MicroNano Technology (CMi) and in the Birck Nanotechnology Center at Purdue University. AlN deposition was performed at OEM Group Inc.

**Author contributions** J.L., H.T. and R.N.W. designed and fabricated the samples. J.L., H.T., J.H. and T.L. tested the samples and fabrication yield. E.L., A.S.R., J.L., G.L., M.H.A. and W.W. performed experiments. J.L., E.L., A.S.R. and G.L. analysed the data. J.L., T.J.K. and S.A.B. wrote the manuscript, with input from others. T.J.K. and S.A.B. initiated and supervised the collaboration.

**Competing interests** T.J.K. is a co-founder and shareholder of LiGenTec SA, a start-up company that is engaged in making Si$_3$N$_4$ nonlinear photonic chips available via foundry service.

**Additional information**

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**Peer review information** Nature thanks Matt Eichenfield and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Extended Data Fig. 1 | Experimental characterization of resonance frequency versus applied voltage. a, Experimental set-up. OSA, optical spectrum analyser; PD, photodiode. b, Resonance tuning data with error bars. The voltage applied to the AlN actuator is varied in the range ±100 V in order to reveal the hysteresis. The standard deviation (s.d.) of the measured frequency at each voltage value is evaluated using the measured frequency with respect to the fitted frequency on the linear curve. The error bars show ±1 s.d. Inset, magnified view highlighting the difference in scale between the observed hysteresis (that is, the frequency difference between two fitted curves) and the error bars. The overall frequency measurement uncertainty is estimated to be below 15 MHz, smaller than the observed hysteresis.
**Extended Data Fig. 2 | Characterization of resonance linewidth and microresonator dispersion.**

**a.** Comparison of loaded resonance linewidths with different applied voltages. No voltage-dependent linewidth change is observed.

**b.** Comparison of microresonator dispersion with different applied voltages. No dispersion change is observed.
Extended Data Fig. 3 | Long-term soliton stabilization via AlN feedback actuation. **a**, Experimental set-up. OSC, oscilloscope; BPF, bandpass filter; FBG, fibre Bragg grating. **b**, Soliton stabilization over 5 h, realized by locking the resonance to the laser and maintaining the soliton detuning. Three selected comb lines that exist for more than 5 h are shown here.
Extended Data Fig. 4 | On-chip generation of PDH error signals using the HBAR modes induced by AlN actuation. a, Experimental set-up. LPF, low-pass filter; Amp., RF power amplifier. b, The measured $S_{21}(\omega)$ response of the AlN actuator on a linear frequency scale. Measurements are taken when the laser is on-resonance and off-resonance. c, PDH error signals modulated at the four HBAR frequencies marked with stars in b.
Extended Data Fig. 5 | Experimental set-ups used to characterize the soliton lidar engine and soliton locking. a, Experimental set-up for the synchronous scan of the laser frequency and the microresonator resonance, using the feed-forward scheme. b, Experimental set-up used to characterize the in-loop phase noise of the beat signal between line no. −1 of the microcomb and line no. −13 of the EO comb. QPSK, quadrature phase shift keying; DSO, digital storage oscilloscope; MZM, Mach–Zehnder modulator; PNA, phase noise analyser.
Extended Data Fig. 6 | Original, unprocessed optical micrograph data used to prepare Fig. 1b in the main text.
Extended Data Fig. 7 | Original, unprocessed SEM data used to prepare Fig. 1c in the main text.