Massively parallel coherent laser ranging using a soliton microcomb

Coherent ranging, also known as frequency-modulated continuous-wave (FMCW) laser-based light detection and ranging (lidar) is used for long-range three-dimensional distance and velocimetry in autonomous driving. FMCW lidar maps distance to frequency using frequency-chirped waveforms and simultaneously measures the Doppler shift of the reflected laser light, similar to sonar or radar and coherent detection prevents interference from sunlight and other lidar systems. However, coherent ranging has a lower acquisition speed and requires precisely chirped and highly coherent laser sources, hindering widespread use of the lidar system and impeding parallelization, compared to modern time-of-flight ranging systems that use arrays of individual lasers. Here we demonstrate a massively parallel coherent lidar scheme using an ultra-low-loss photonic chip-based soliton microcomb. By fast chirping of the pump laser in the soliton existence range of a microcomb with amplitudes of up to several gigahertz and a sweep rate of up to ten megahertz, a rapid frequency change occurs in the underlying carrier waveform of the soliton pulse stream, but the pulse-to-pulse repetition rate of the soliton pulse stream is retained. As a result, the chirp from a single narrow-linewidth pump laser is transferred to all spectral comb teeth of the soliton at once, thus enabling parallelism in the FMCW lidar. Using this approach we generate 30 distinct channels, demonstrating both parallel distance and velocity measurements at an equivalent rate of three megapixels per second, with the potential to improve sampling rates beyond 150 megapixels per second and to increase the image refresh rate of the FMCW lidar by up to two orders of magnitude without deterioration of eye safety. This approach, when combined with photonic phase arrays based on nanophotonic gratings, provides a technological basis for compact, massively parallel and ultrahigh-frame-rate coherent lidar systems.

In recent years, interest in lidar has been fuelled by the development of autonomous driving, which requires the ability quickly to recognize and classify objects under fast-changing and low-visibility conditions. Lidar can overcome the challenges of camera imaging, such as those associated with weather conditions or illumination, and has been used successfully in nearly all recent demonstrations of high-level autonomous driving. Generally, laser ranging is based on two different principles: time-of-flight and coherent ranging. In time-of-flight lidar, the distance of an object is determined on the basis of the delay of reflected laser pulses. To increase the speed of image acquisition, modern systems employ an array of individual lasers (as many as 256) to replace slow mechanical scanning to replace slow mechanical scanning. The velocity information can be inferred only by comparing subsequent images, a process prone to errors caused by vehicle motion and interference.

A different principle is that of FMCW lidar. In this case a laser that is linearly chirped is sent to an object, and the time–frequency information of the return signal is determined by delayed homodyne detection. The maximum range is therefore limited not only by the available laser power but also by the coherence length of the laser. Assuming a triangular laser scan (over an excursion bandwidth \(B\) with period \(T\); see Fig. 1e), the distance information (that is, the time of flight, \(\Delta t\)) is mapped to a beat note frequency, that is, \(f = \Delta t \times 2B/T\). For a static object, owing to the relative velocity \(v\) of an object, the returning laser light is detected with a Doppler shift \(\Delta f_D = k\cdot v/\pi\), where \(k\) is the wavevector and \(v\) is the velocity of the illuminated object. As a result, the homodyne return signal for a moving object is composed of two frequencies for the upwards and downwards laser scan, that is, \(f_0 = f + \Delta f_0\) and \(f_0 = -f + \Delta f_0\). From the measured beat notes during one period of the scan, one can therefore determine both the distance and relative velocity of an object (see Fig. 1e). The latter greatly facilitates image processing and object classification, particularly relevant to traffic. Moreover, FMCW lidar increases the photon flux used for ranging, hence
increasing the sensitivity and range compared to time-of-flight lidar systems, which at present rely on sequential switching of laser diode arrays. Furthermore, coherent lidar is superior to time-of-flight implementations in low-visibility and high-background-light conditions, culminating in achievements such as detecting the distance to objects engulfed in flames, because delayed homodyne detection makes it almost impervious to interference and malicious remote attacks. Despite these advantages, coherent ranging suffers from the stringent requirement of narrow linewidth, as well as fast and linear frequency chirping, which makes massively parallel implementations, as used in time-of-flight lidar, challenging.

Concept of soliton-based parallel FMCW ranging
Here we demonstrate a massively parallel coherent FMCW source based on a soliton microcomb integrated on a photonic chip. Specifically, we show that agile chirping of the pump laser frequency retains the soliton state and leads to simultaneous chirping of all comb teeth, where $\mu$ denotes the mode number comprising the soliton. The principles of massively parallel coherent lidar based on soliton microcombs are illustrated in Fig. 1a. The underlying idea is to transfer the chirp of a prepared frequency-modulated lidar source to multiple comb sidebands by using it to generate a dissipative Kerr soliton (DKS). In the time domain (see Fig. 1a), we modulate the underlying soliton carrier frequency, while minimizing changes of the pulse envelope and repetition rate. In the frequency domain, this corresponds to a concurrent modulation of the optical frequency of each comb tooth around its average value (that is, a modulation of the frequency comb’s carrier-envelope frequency). This effect, when combined with triangular frequency modulation of a narrow linewidth pump laser, generates a massively parallel array of independent FMCW lasers. When dispersing the channels using diffractive optics, as illustrated in Fig. 1b, each...
FMCW systems, which achieve better distance precision and acquisition speeds, yet exhibit a limited ambiguity range dictated by the pulse repetition rate, and demand the relative laser-cavity detunings $\Delta_1 = 1.2$ GHz and $\Delta_2 = 2.9$ GHz. Increasing the detuning, we observe the well known bistable cavity resonance (blue shaded area) in the soliton existence range directly reveals the relative laser-cavity detuning (Fig. 2). The inclusion of stimulated Raman scattering into the simulation reveals a modulation of the repetition rate of up to 10 MHz during the frequency-modulated cycle. The stability chart of the soliton microcomb for the device used in the lidar experiments. The soliton existence range is highlighted in green and confined by the stability of the soliton solution. MI, modulation instability.

Figure 2a shows the optical spectra of the DKS at the extrema of the frequency-modulated DKS generation. The laser is tuned through the modulation instability region (blue shaded area) and the breathing region (red shaded area) into the soliton state and triangular frequency modulation is imprinted at a chirp rate of $(d\Delta/d\tau) = 1.7 \times 10^{16}$ Hz$^{-2}$. The inclusion of stimulated Raman scattering into the simulation reveals a modulation of the repetition rate of up to 10 MHz during the frequency-modulated cycle. Simulated stability chart of the soliton microcomb for the device used in the lidar experiments. The soliton existence range is highlighted in green and confined by the stability of the soliton solution. MI, modulation instability.

This scheme leverages three key properties of DKS; the large (that is, gigahertz) existence range of the soliton, the fact that the repetition rate changes associated with laser scanning are small, and the ability, as detailed below, to very rapidly sweep between stable operating points without destroying the soliton state or deterioration of the chirp linearity. Homodyning the reflected signal with the original comb teeth channel-by-channel, using low-bandwidth detectors and digitizers, allows the coherent ranging signal to be recovered and reconstructed for each comb line $\mu$ simultaneously, yielding velocity and distance ($v_\mu$, $\Delta_\mu$) for each pixel. The scheme presented here thus enables true parallel detection of dozens and potentially hundreds of pixels simultaneously. Hence, massively parallel (and high-speed) coherent lidar becomes possible, while requiring only a single well controlled laser to generate the carrier-frequency chirped soliton. This is in contrast with dual-frequency-comb coherent time-of-flight systems23,24, which achieve better distance precision and acquisition speeds, yet exhibit a limited ambiguity range dictated by the pulse repetition rate, and are challenging to parallelize because the whole frequency comb must illuminate a single pixel. In a similar fashion, frequency-modulated DKS generation. The laser is tuned through the modulation instability region (blue shaded area) and the breathing region (red shaded area) into the soliton state and triangular frequency modulation is imprinted at a chirp rate of $(d\Delta/d\tau) = 1.7 \times 10^{16}$ Hz$^{-2}$. The inclusion of stimulated Raman scattering into the simulation reveals a modulation of the repetition rate of up to 10 MHz during the frequency-modulated cycle. Simulated stability chart of the soliton microcomb for the device used in the lidar experiments. The soliton existence range is highlighted in green and confined by the stability of the soliton solution. MI, modulation instability.
detuning between the cavity resonance and the continuous-wave pump laser. We next perform numerical simulations based on the Lugiato–Lefever equation \(^{27,28}\), which demonstrate the ability of the DKS state to transfer the chirp from the pump laser to all comb teeth (see Fig. 2c). The numerical laser scan is started at \(\Delta = -0.4\) GHz and the detuning \(\Delta\) is subsequently increased with a linear chirp rate of \(|d\Delta/dt| = 4 \times 10^4\) Hz/s, tuning past the modulation instability region and exciting a single soliton. Hereafter, the linear laser scan is inflected and a symmetric triangular frequency modulation with equal chirp rate is continued. If stimulated Raman effects \(^{21,22}\) and higher-order dispersion are neglected, the repetition rate remains almost perfectly constant and the frequency chirp is faithfully transduced to each comb line. Even more surprisingly, the inclusion of stimulated Raman scattering and third-order dispersion effects induces only a small repetition rate mismatch \(\Delta f_{\text{rep}}\) of 20.6 MHz per 1.7 GHz of laser tuning, which is observed as acceleration and deceleration of the soliton in the cavity (see Fig. 2d, bottom). The fundamental limit for the tuning speed \(d\Delta/dt < (\kappa/2\pi)^2\) is set by the cavity photon decay rate \(\kappa\).

The linear dependence \(df_{\text{rep}}/d\Delta = (\Omega_0/2\pi\Delta)(D_2/D_1)\), where \(D_1/2\pi\) is the cavity free-spectral range and \(D_2/2\pi\) is the second-order dispersion, results in a channel-dependent frequency excursion \(B_s\) and, hence, a constant rescaling factor of the measured lidar distance, which we can determine during calibration. Only nonlinear dependencies of the pulse repetition rate \(f_{\text{rep}}\) on the detuning \(\Delta\) from either the Raman shift \(^{20}\) or multimodal interactions \(^{29}\), actually degrade the linearity of the transduced chirp. The maximum detuning, which still supports stable DKS generation, is determined by the input pump power \(^{20}\), which in turn is fundamentally limited by a Raman instability \(^{20}\).

**Characterization of parallel FMCW lidar source**

Next, we experimentally demonstrate the ability to faithfully transfer the pump laser chirp to the individual comb teeth (see Fig. 3). Details of the experimental setup for heterodyne characterization, linearization of the triangular frequency-modulation patterns, and transduction data analysis are described in the Methods. Results for the comb teeth at 195 THz (\(\mu = +20\)) and modulation frequencies \(1/T\) from 100 kHz to 10 MHz are depicted in Fig. 3b and in Extended Data Fig. 3. The frequency excursion bandwidth \(B_s\) increases linearly with the channel number \(\mu\) (see Fig. 3e) at a rate of \(dB_s/d\mu = 22.15\) MHz in agreement with the predictions from numerical simulations including the Raman self-frequency...
We define the chirp nonlinearity as the deviation of the measured instantaneous frequency from a perfectly symmetric triangular frequency-modulation scan, estimated with least-squares fitting, and depict results for the pump and two comb teeth in Fig. 3c (bottom). Narrow peaks of the chirp nonlinearity are attributed to single-mode dispersive waves. We do not observe intermode breathing of the soliton in the present system. The channel-dependent root-mean-square nonlinearity is depicted in the inset of Fig. 3e and remains below 1/500 of the full frequency excursion for all channels at 100-kHz modulation frequency. The frequency-dependent transduction of the frequency modulation from the pump laser to the DKS teeth is calculated from the transduced chirps and is plotted in Fig. 3d. We find a lower bound for the 3-dB modulation frequency cutoff of 40 MHz, which corresponds to a maximum...
Parallel ranging, velocimetry and 3D imaging

Next, we perform a proof-of-concept demonstration of the massively parallel lidar system. The calibrated frequency-modulated microcomb is split (90/10) into a signal path, which is spectrally dispersed around the circumference of the flywheel by a transmission grating (966 lines per millimetre), and a local oscillator path. The spectral channels of the reflected signal and the local oscillator are isolated using a bidirectional arrayed waveguide grating. The results of parallel distance and velocity measurement including standard deviations over 100 frequency-modulated periods for the static wheel are displayed in Fig. 4e, g. Channels beyond 195.2 THz are not observed with sufficient signal-to-noise ratio, because of limited amplification bandwidth. The measurement imprecision over 25 spectral channels is below 1 cm, comparable with state-of-the-art time-of-flight lidar systems and can be improved by using more broadband chirps. Small systematic offsets on the centimetre scale are associated with the lengths of the fibre pigtails in the demultiplexers and switches. The results for the wheel spinning at 228 Hz are depicted in Fig. 4f, resolving the position dependency of the projected velocity around the circumference of the wheel (see Fig. 4d). The measurement accuracy in case of the spinning wheel is limited by vibration. The equivalent distance and velocity sampling rate of the 30 independent channels is 3 megapixels per second.

Last, we demonstrate parallel 3D imaging of 30 channels spectrally dispersed with a transmission grating and concurrently illuminating a target composed of two sheets of white paper spaced by 11 cm with the EPFL university logo cut out in the front plane (see Fig. 5). The target profile is imaged by translation of the beams in the vertical direction with a 45° steering mirror, and depicted in Fig. 5b. The detection is monostatic and the co-observed backreflection from the collimation lens serves as the zero-distance plane in the measurement. Target points detected in the back plane are clearly separated, owing to the centimetre-level distance precision and accuracy observed on all 30 FMCW channels (see Fig. 5c, d) and highlighted as filled points.

Discussion and conclusion

Thus we have described a method for massively parallel coherent lidar using photonic chip-based soliton microcombs. It enables us to reproduce arbitrary frequency chirps of the narrow linewidth pump laser onto all comb teeth that compose the soliton at speeds beyond $10^{17}$ Hz, and has the potential to greatly increase the frame rate of imaging coherent lidar systems via parallelization. In contrast to earlier works in frequency-comb-based lidar\cite{21,22,23}, the comb teeth in parallel FMCW lidar are spatially dispersed with diffractive optics and separately measure distances and velocities in a truly parallel fashion. Assuming a setup similar to that of ref. \cite{24}, that is, 179 carriers with 50-GHz spacing in the C+L telecommunications wavelength bands (1,530–1,610 nm), we expect aggregate pixel measurement rates of 17.9 megapixels per second for 100-kHz modulation frequency and 179 megapixels per second for 1-MHz modulation frequency, well beyond the present technologies of long-range time-of-flight and FMCW lidar systems.
Although the residual nonlinearity and slow power modulation of the comb sidebands during the frequency chirp only weakly influences the distance and velocity evaluation, we emphasize that both effects can be avoided entirely if both the laser and cavity are modulated in unison.36. Similarly, the laser can be self-injection-locked to the modulated cavity, which can furthermore extend the laser coherence length substantially.37,38. Promising actuation technologies include recently developed high-bandwidth and energy-efficient integrated electro-optical39 and piezoelectrical actuators.40.

Moreover, by virtue of the laser line separations, our concept is compatible with nanophotonics-based gratings for beam separation and could greatly simplify optical phased array systems,12 wherein one axis of beam separation is provided by the nanophotonic grating and a second axis is provided by integrated phase shifters. Furthermore, this concept alleviates problems with eye safety, as the light is dispersed over multiple detection pixels at all times, similar to time-of-flight light systems, yet avoids the problems associated with the excessive peak powers of high-energy pulsed light sources. Finally, spectrally multiplexed detection can also be carried out in a dual-comb approach, whereby the second comb scans in unison with the first, but has a different repetition rate, which removes the need for demultiplexing and individual detection of the comb lines. It should be noted that (resonant) electro-optical frequency combs34,40 based on LiNbO$_3$ also provide a platform in which the approach presented here could be realized. Hence, we conclude that microcombs, combined with concurrent advances in chip-scale lasers, optical beamforming structures, and hybrid electro-optical integration provide a path towards rapid, precise and simultaneously long-range coherent lidar modules suitable for industrial, automotive and airborne applications demanding high-speed 3D imaging in excess of ten megapixels per second.

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Methods

Sample details and fabrication
Integrated Si$_3$N$_4$ microresonators are fabricated with the photonic damascene process$^{41}$, deep-ultraviolet stepper lithography$^{42}$ and silica preform reflow$^{43}$. The waveguide cross-section is 1.5 μm wide and 0.82 μm high, with anomalous second-order dispersion of $D_{/2π} = 1.13$ MHz and third-order dispersion parameter of $D_{/2π} = 576$ Hz, where the positions of the resonance frequencies close to the pumped resonance are expressed by the series $ω_{0} + \sum_{n} D_{/2π} \mu_{n} / n$. The ring radius is 228.43 μm and results in a resonator free-spectral-range of $D_{/2π} = 98.9$ GHz, which is chosen to match the standard 100-GHz telecommunication channel grid. The resonator is operated in the strongly overcoupled regime with an intrinsic loss rate $k_{2π}/2π = 15$ MHz and bus waveguide coupling rate $k_{2π}/2π = 100$ MHz. Operation in the strongly overcoupled regime has the advantage of suppressing thermal nonlinearities during tuning as well as increasing the power per comb line before and optical signal-to-noise ratio after post-amplification. Input and output coupling of light to and from the fundamental transverse electric (TE) mode of the photonic chip is facilitated with double inverse tapers$^{44}$ and lensed fibres.

Frequency-modulated soliton microcomb generation
We set up a frequency-agile pump laser for soliton generation using a continuous-wave external cavity diode laser coupled into an electro-optical phase modulator for measurement of the relative laser cavity detuning, and dual Mach–Zehnder modulator (single sideband modulator) biased to single sideband modulation, which is driven by a frequency-agile voltage controlled oscillator (VCO, 5–10 GHz) and an arbitrary function generator. The continuous-wave laser is amplified to 1.7 W and 1 mW is split off for chirp linearization in a separate imbalanced Mach–Zehnder fibre interferometer (MZI) for chirp linearization purposes$^{45,46}$. The DKS$^{19,20}$ is generated by coupling the frequency-modulated pump laser onto the photonic chip and tuning of the laser into resonance and single soliton state using the established piezo tuning scheme$^{26}$. The detuning with respect to the Kerr shifted cavity resonance and the bistable soliton response is monitored using a vector network analyser driving a weak phase modulation via an inline electro-optical-modulator$^{26}$ and an optical spectrum analyser. The generated soliton is coupled back into the optical fibre, the residual pump light is filtered and the soliton pulse train is amplified with a gain-flattening erbium-doped fibre amplifier. The repetition rate of the soliton pulse train is 99 GHz and the cavity resonance is aligned to the telecom channel C30 at a wavelength of 1,553.3 nm using a thermo-electric cooling device located below the active chip. Although it is possible to directly modulate all comb teeth post-DKS generation, this method suffers from excess insertion loss of the single sideband modulation around 15 dB, which severely degrades the optical signal-to-noise ratio after post-amplification. Even more critically, the internal MZIs of the single-sideband modulator are wavelength-dependent and require precise direct-current biasing to suppress the unwanted carrier and higher-order sidebands, which limits the usable optical bandwidth for direct single sideband modulation of the soliton comb. Our scheme of single sideband modulation of the soliton pump laser has the advantage that the fundamental carrier and unwanted sidebands are not transduced in the cavity and no sidebands on the comb teeth appear. Moreover, our scheme works irrespective of the choice of laser and microresonator actuation schemes, especially established FMCW sources that are based on frequency-agile diode lasers. The residual effects of the cavity, limiting both the chirp range and inducing a small nonlinearity in the transduction can be alleviated strongly by concurrent actuation of the cavity and the diode laser$^{39}$, with direct injection locking of the laser to the modalized cavity constituting an especially compact and technologically promising implementation scheme$^{46,47}$.

Linearization and calibration
Frequency-modulated lidar requires perfectly linear chirp ramps to achieve precise and accurate distance measurements$^8$. We implemented a digital pre-distortion circuit in order to minimize the chirp nonlinearity of the pump frequency sweep, similar to prior implementations$^{48}$. The optimization procedure was applied in two configurations to measure the pump frequency chirp, either via heterodyne with a reference laser (see Fig. 3), or via delayed homodyne detection in an imbalanced MZI. The length difference of the calibration MZI arms (12.246 m) is determined using the electro-optical phase modulator and vector network analyser and fitting the $\sin^2$ spectral response function of the MZI. The setup and optimization results for this method are detailed in Extended Data Fig. 1. The chirp is applied to the continuous-wave laser with a VCO-driven single sideband modulator. The VCO is initially driven by a simple triangular function generated using the arbitrary function generator. The driving voltage is then iteratively corrected to improve the chirp linearity. After modulation, a fraction of the light is picked up to generate a beat note with a reference external cavity diode laser. The downmixed laser frequency is sampled on a digital sampling oscilloscope (20 gigasamples per second) and digitally processed to perform a short-term Fourier transform followed by peak detection. The measured frequency evolution is fitted with a perfect triangular function having a fixed target frequency excursion. This allows the deviation from this desired frequency chirp to be assessed. The frequency deviation is then converted to voltage—after computing the average voltage-to-frequency coefficient of the VCO—and then added to the current tuning function of the arbitrary function generator. This procedure effectively addresses the nonlinearity of the VCO, as shown in Extended Data Fig. 1b–e. The optimization procedure was applied successfully at different tuning speeds (10 kHz–10 MHz), as shown in Extended Data Fig. 2. However, with increasing tuning speed, the residual root-mean-square deviation increases, which we attribute to the limited tuning bandwidth of the VCO.

Heterodyne characterization of frequency-modulated soliton microcomb
Heterodyne characterization of the transduced modulation is carried out to avoid possible ambiguities of delayed homodyne detection by catch high-frequency noise components obscured in low bandwidth detection. The spectral channels are isolated using a commercial telecommunication wavelength-division demultiplexer based on planar arrayed waveguide gratings and superimposed on a high-bandwidth (10 GHz) balanced photodetector. The data are recorded on a high-bandwidth balanced photodetector and a fast realtime sampling oscilloscope. Modulation frequencies span from 10 kHz to 10 MHz in our study and are limited by the actuation bandwidth of the arbitrary function generator and VCO. The total measurement duration is between 0.5 ms (10 kHz) and 30 μs (10 MHz). The instantaneous frequency is determined via short-time Fourier transform using a 4th-order Nuttall window and in the case of the pump channel (193 THz) is linearized by applying iterative predistortion of the VCO input (see Extended Data Fig. 1). The resolution bandwidth $\Delta f$ of the transform window is adjusted to minimize the effective linewidth of the chirped signal:

$$\Delta f = \sqrt{\frac{2B}{T}}$$  (1)

By tuning the second external cavity diode laser close to the chip and with a high modulation depths, we can separately measure the transduced frequency modulation patterns for each comb sideband within the bandwidth of the demultiplexer. The resulting time frequency maps for the modulation frequencies 100 kHz and 10 MHz across five modulation periods are depicted in Extended Data Fig. 7.
The experimental setup is illustrated in Fig. 4a. The frequency modulation of the transduced chirp. A fine analysis reveals three effects. For low modulation frequencies, weak even-order sidebands arise, which we attribute to the hysteresis effect, which accompanies the generation of single mode dispersion waves9,12, essentially introducing a small asymmetry in the transduced chirp.

Parallel velocimetry and ranging

The experimental setup is illustrated in Fig. 4a. The frequency modulation of the microcomb pump are adjusted to 100 kHz and 1.7 GHz, respectively. The frequency-modulated comb is amplified with a gain-flattened erbium-doped fibre amplifier and split into signal (90%) and local oscillator (10%) paths. A total power of 350 mW is emitted from the collimator, which equates to between 5 mW and 20 mW per comb line. A transmission grating (966 lines per millimetre) spectrally disperses the individual signal comb lines along the circumference of the flywheel. Normal incidence reflection of the flywheel is obtained by the frequency-modulated microcomb sideband at 193.8 THz. A bistatic detection with separate collimators for the transmit and receive paths is chosen to minimize spurious backreflection in the fibre components. The back-reflected signal and local oscillator comb lines are spectrally separated in the demultiplexer and superimposed on a balanced photodetector for detection. Two 1 × 40 mechanical optical switches are installed with the demultiplexers to allow individual channels to be measured sequentially, removing the requirement to provide 30 balanced photodetectors and analogue-to-digital converters. The total optical loss budget of the demultiplexing network is around 5 dB per channel and could be reduced by co-integration on the photonic chip. We stress that in all measurements illuminating and receiving light and demultiplexing the pixels are done simultaneously. Hence, any additional noise and crosstalk between the channels would be detected in our setup. However, our system is impervious to crosstalk and interference between the channels, because of the spatial channel separation, in contrast to simple spatial channel separation15, which requires sequential operation. Our current setup utilizes discrete telecommunications fibre components and optical switches for the detection, but we emphasize that high-performance integrated photonic solutions for many-channel dense wavelength division multiplexing communications have been demonstrated16 and can be integrated on the SiNx photonic chip with performance comparable to that of the commercial telecommunication components employed here16,17. The calibration of the channel-dependent frequency excision bandwidth for the ranging experiments is performed using a second MZI (8.075 m; see Extended Data Fig. 6). The calibration curve is detected once before the start of the measurements and assumed constant throughout. The distance and velocity precision and accuracy of the system are determined using a small flywheel (radius 20 mm) mounted on a fast direct-current motor spinning at up to 228 Hz (see Fig. 4). The data analysis is performed with a simple Fourier transform accounting for a constant 353 ns delay between the arbitrary function generator and the lidar lasers, which is mainly obtained from the optical fibre lengths of the erbium-doped fibre amplifiers. We apply a 4th-order Blackman–Harris type window function with effective resolution bandwidth 330 kHz. This resolution bandwidth corresponds to a range bin width of 7.9 cm (192.1 THz) to 5.9 cm (194.9 THZ), in accordance with the FMCW fundamental range resolution $\Delta x = c/2B$. Two spectra corresponding to the upwards and downwards slopes of the frequency chirp are separately transformed within each FMCW period and we apply Gaussian peak fitting to determine the peak frequency in each spectrum. We determine the statistical distance error by calculating the standard deviation of 100 consecutive distance measurements, which deviate by less than 1 cm from the mean. Further improvements, especially in long-range detection, could be achieved using active demodulation analysis18. The residual nonlinearity broadens the detected beat notes and reduces the signal-to-noise ratio and power efficiency of the system. We estimate that an optimized version of our architecture with concurrent tuning of the resonator and laser would feature improved precision and detection performance by up to one order of magnitude.

Demonstration of parallel imaging

The optical setup is depicted in Fig. 5a, wherein the optical receiver, demultiplexers and detectors are omitted for brevity, but are set up as depicted in Fig. 4a. The target is composed of two sheets of white paper spaced by 11.5 cm. The EPFL University logo (width 7.5 cm, height 22.7 cm) is cut from the first sheet and oriented vertically. The FMCW lidar channels are dispersed horizontally using a transmission grating of 966 lines per millimetre and directed to the target with a 45° steering mirror. A monostatic detection scheme using an optical circulator and single collimator (Fig. 1) is chosen. The detector aperture is increased by placing a 75-cm focal length lens 1 m away from the 4 mm collimator and behind the grating. We note that modal interactions with the fundamental transverse magnetic (TM) mode strongly increase the power fluctuation of channels at 195.2 THz and 195.3 THz and spoils their use in frequency-modulated lidar experiments by shortening the effective sampling length.

Data availability

The data used to produce the plots within this paper are available at https://doi.org/10.5281/zenodo.3603614.

Code availability

The code used to produce the plots within this paper is available at https://doi.org/10.5281/zenodo.3603614.

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Author contributions A.L. and J.R. conducted the various experiments and analysed the data. E.L. assisted with laser linearization, W.W. performed the numerical simulations, A.L. designed the samples and J.L. fabricated the samples. All authors discussed the manuscript. J.R., T.J.K., M.K. and E.L. wrote the manuscript. T.J.K. supervised the work and conceived the experiment.

Competing interests T.J.K. is a co-founder and shareholder of LiGenTec SA, a start-up company that is engaged in making SiN4 nonlinear photonic chips available via foundry service.

Additional information Correspondence and requests for materials should be addressed to T.J.K. Reprints and permissions information is available at http://www.nature.com/reprints.
Extended Data Fig. 1 | Pump frequency sweep linearization via the heterodyne method. **a**, Setup for pump-laser frequency measurement via heterodyne beat note and chirp linearization feedback. **b**, Initial frequency modulation, when the VCO is driven with a triangular ramp. The measured frequency is compared with the targeted ideal modulation. The ramp frequency is 100 kHz. **c**, Final triangular frequency modulation pattern, after four iterations. **d**, Evolution of the root-mean-square (RMS) frequency deviation during the optimization loop. **e**, Evolution of the deviation between measurement and target sweep, at each iteration of the loop.
Extended Data Fig. 2 | Linearization results at different modulation frequencies. a, c, e. The evolution of the root mean-square frequency deviation during the optimization loop for modulation frequencies of 10 kHz, 1 MHz and 10 MHz, respectively. b, d, f. Corresponding evolution of the deviation between the measurement and the target sweep, at each iteration of the loop.
Extended Data Fig. 3 | Channel-by-channel analysis of heterodyne chirp characterization. **a**, Time–frequency maps obtained with short-time Fourier transform of the heterodyne beat detection of the individual FMCW channels. Top left to bottom right panels denote optical carriers between 192.1 THz and 196 THz. Modulation frequency is 100 kHz. The pump channel at 193 THz is outlined in purple. **b**, As for **a**, but for modulation frequency 10 MHz.
Extended Data Fig. 4 | Frequency-dependent transduction of carrier modulation from pump to comb sidebands. a, Time-dependent frequency of pump laser at 193 THz (grey) and 195 THz comb sideband (μ = 20, dark green) and modulation frequency 100 kHz. b, As for a, but for modulation frequency 10 MHz. c, Power spectral density of frequency modulation $S_F$ for pump (grey) and sideband (dark green). The markers denote the positions of harmonics, which are used in the transduction analysis. The lower panel shows the power spectral density of sideband frequency modulation harmonics normalized to the corresponding modulation power spectral density of the pump laser (see Fig. 3). d, As for c, but for modulation frequency 10 MHz.
Extended Data Fig. 5 | Pump frequency sweep linearization via the delayed homodyne method. a, Setup for pump-laser frequency measurement via delayed homodyne detection and chirp linearization feedback. Calibration of the MZI is performed by fitting the frequency-dependent phase modulation response of the MZI. b, Initial frequency modulation, when the VCO is driven with a triangular ramp, determined using a Hilbert transform. The measured frequency is compared with the targeted ideal modulation. The ramp frequency is 100 kHz. The red-shaded regions around the extremal points are excluded from the linearization update. c, Final triangular frequency modulation pattern, after 20 iterations. Convergence achieved after four iterations. d, Evolution of the root-mean-square frequency deviation during the optimization loop. e, Evolution of the deviation between measurement and target sweep, at each iteration of the loop.
Extended Data Fig. 6 | Calibration of channel dependent frequency excursion bandwidth for distance and velocity measurements.

**a**. Measurement setup. The linearized frequency-modulated microcomb (see Extended Data Fig. 5 for setup schematic) is amplified and individual channels are selected by connecting the local oscillator path of the measurement setup to a calibrated imbalanced MZI (8.075 m). **b**. The top panel shows the frequency-exursion bandwidth \( B_{\mu} \) determined from independent measurement of the length of imbalanced MZI. Linear fit related to Raman self-frequency shift \( \Omega_R \). The bottom panel shows the residuals of the linear fit.
Extended Data Fig. 7 | Channel-by-channel analysis of proof-of-concept lidar demonstration. 

**a**, Time-frequency maps obtained with short-time Fourier transform of the delayed homodyne beat detection of the individual FMCW channels back-reflected from the rotating flywheel. Top left to bottom right panels denote optical carriers between 192.1 THz and 195.2 THz. The pump channel at 193 THz is outlined in purple. Modulation frequency is 100 kHz. 

**b**, As for **a**, but for static flywheel.