doi:10.1038/nature22387

Microresonator-based solitons for massively parallel coherent optical communications

Pablo Marin-Palomo[1]*, Juned N. Kemal[1]*, Maxim Karpov[2]*, Arne Kordts[2], Joerg Pfeifle[1], Martin H. P. Pfeiffer[2], Philipp Trocha[1], Stefan Wolf[1], Victor Brasch[2], Miles H. Anderson[2], Ralf Rosenberger[1], Kovendhan Vijayan[1], Wolfgang Freude[1,3], Tobias J. Kippenberg[2] & Christian Koos[1,3]

Solitons are waveforms that preserve their shape while propagating, as a result of a balance of dispersion and nonlinearity[1,2]. Soliton-based data transmission schemes were investigated in the 1980s and showed promise as a way of overcoming the limitations imposed by dispersion of optical fibres. However, these approaches were later abandoned in favour of wavelength-division multiplexing schemes, which are easier to implement and offer improved scalability to higher data rates. Here we show that solitons could make a comeback in optical communications, not as a competitor but as a key element of massively parallel wavelength-division multiplexing. Instead of encoding data on the soliton pulse train itself, we use continuous-wave tones of the associated frequency comb as carriers for communication. Dissipative Kerr solitons (DKSs)[3,4] (solitons that rely on a double balance of parametric gain and cavity loss, as well as dispersion and nonlinearity) are generated as continuously circulating pulses in an integrated silicon nitride microresonator[5] via four-photon interactions mediated by the Kerr nonlinearity, leading to low-noise, spectrally smooth, broadband optical frequency combs[6]. We use two interleaved DKS frequency combs to transmit a data stream of more than 50 terabits per second on 179 individual optical carriers that span the entire telecommunication C and L bands (centred around infrared telecommunication wavelengths of 1.55 micrometres). We also demonstrate coherent detection of a wavelength-division multiplexing data stream by using a pair of DKS frequency combs—one as a multi-wavelength light source at the transmitter and the other as the corresponding local oscillator at the receiver. This approach exploits the scalability of microresonator-based DKS frequency comb sources for massively parallel optical communications at both the transmitter and the receiver. Our results demonstrate the potential of these sources to replace the arrays of continuous-wave lasers that are currently used in high-speed communications. In combination with advanced spatial multiplexing schemes[7,8] and highly integrated silicon photonic circuits[9], DKS frequency combs could bring chip-scale petabit-per-second transceivers into reach.

The first observation of solitons in optical fibres[2] in 1980 was immediately followed by large research efforts to harness such waveforms for long-haul communications[1]. In these schemes, data were encoded on soliton pulses via amplitude modulation using on–off keying. However, even though the viability of the approach was experimentally demonstrated by transmission over one million kilometres[10], soliton-based communications was ultimately hindered by difficulties in achieving shape-preserving propagation in real transmission systems[1] and by the fact that nonlinear interactions intrinsically prevent dense packing of soliton pulses in either the time or the frequency domain. Moreover, with the advent of wavelength-division multiplexing (WDM), line rates in long-haul communication systems could be increased by parallel transmission of data streams with lower symbol rates, which are less sensitive to dispersion. Consequently, soliton-based communication schemes moved out of focus over the past two decades.

More recently, it has been suggested that frequency combs could revolutionize high-speed optical communications, offering tens or even hundreds of well-defined narrowband optical carriers for massively parallel WDM[8,11,12]. Unlike carriers derived from a bank of individual laser modules, the tones of a comb are intrinsically equidistant in frequency, thereby eliminating the need for individual wavelength control and for inter-channel guard bands[8,12]. In addition, when derived from the same comb source, stochastic frequency variations of optical carriers are strongly correlated, permitting efficient compensation of impairments caused by nonlinearities of the transmission fibre[13].

For application in optical communications, frequency comb sources must be compact. In recent years, various chip-scale comb sources have been demonstrated[14–16] that enable transmission of WDM data streams with line rates[16] of up to 12 Tbit s^{-1}. However, transmission at higher line rates requires more carriers and lower noise levels, and still relies on spectral broadening of narrowband seed combs using dedicated optical fibres[8,11,12] or nanophotonic waveguides[17]. In addition, generating uniform combs with a broadband spectral envelope often requires delicate dispersion management schemes, usually in combination with intermediate amplifiers[11]. Such schemes are difficult to miniaturize and are not readily amenable to chip-scale integration. Moreover, with a few exceptions at comparatively low data rates[18], all advanced comb-based transmission experiments exploit the scalability advantages only at the transmitter, not at the receiver, where individual continuous-wave lasers are still used as optical local oscillators for coherent detection.

Here we show that DKSs[3], generated in integrated photonic microresonators[6] via Kerr-nonlinear four-photon interactions, provide highly stable broadband frequency combs that can overcome the scalability limitations of massively parallel optical transmission at both the transmitter and the receiver. Microresonator-based Kerr comb sources[19,20] have advantages such as a small footprint (the physical area covered by the comb source), a large number of narrow-linewidth optical carriers, and line spacings of tens of gigahertz, which can be designed to fit established WDM frequency grids. However, although these advantages have been recognized, previous transmission experiments[21] were limited to aggregate line rates of 1.44 Tbit s^{-1} owing to strong irregularities of the optical spectrum associated with the specific Kerr comb states.

These limitations can be overcome by using DKS combs generated in a continuous-wave-driven microresonator. The technique exploits four-wave mixing, a nonlinear optical process that converts two pump photons into a pair of new photons. In a microresonator, the strength of this nonlinear interaction is given by the single-photon Kerr

[1]Institute of Photonics and Quantum Electronics (IPQ), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany. [2]Laboratory of Photonics and Quantum Measurements (LPQM), École Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland. [3]Institute of Microstructure Technology (IMT), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany.
*These authors contributed equally to this work.

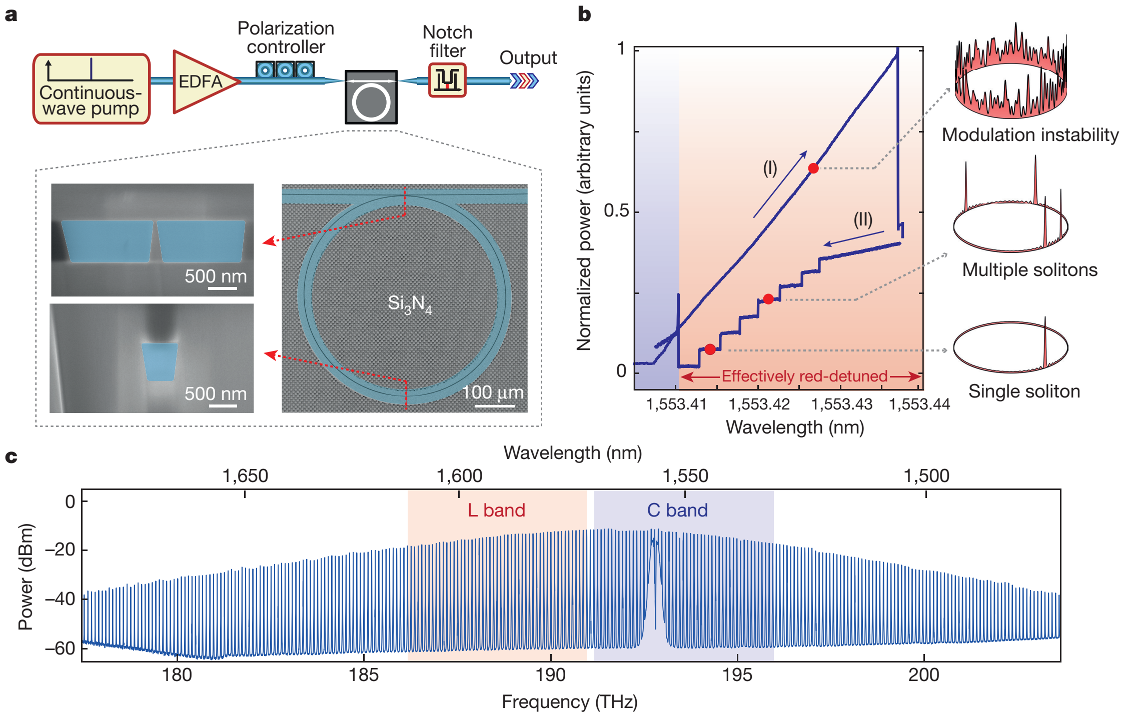

Figure 1 | Generation of broadband frequency combs using DKSs in high-*Q* silicon nitride (Si_3N_4) microresonators. a, Principle of soliton frequency comb generation. The integrated photonic microresonator is pumped by a tunable continuous-wave laser that is amplified by an erbium-doped fibre amplifier (EDFA). Lensed fibres are used to couple light to the chip. A fibre polarization controller is used to optimize the power in the waveguide. After the microresonator, a notch filter suppresses the remaining pump light. The insets show scanning electron microscopy images of a Si_3N_4 microresonator with a radius of 240 µm. Right inset, top view. The checker-board pattern results from the photonic Damascene fabrication process[29] (Methods). Left insets, cross-sections of the resonator waveguide (indicated by the dashed red arrows; dimensions, 0.8 µm × 1.65 µm) at the coupling point (top) and at the tapered section (bottom; dimensions, 0.8 µm × 0.6 µm). The tapered section is used for suppressing higher-order modes[33] while preserving a high optical quality factor ($Q \approx 10^6$; see Methods). **b**, Pump tuning method for soliton generation in an optical microresonator, showing the evolution of the comb power that is generated versus the wavelength of the pump laser: (I) the pump laser is tuned over the cavity resonance from the blue-detuned regime (blue shading), in which high-noise modulation-instability combs are observed, to the red-detuned regime (red shading), in which bistability of the cavity enables the formation of soliton states (here a multiple-soliton state); (II) after a multiple-soliton state is generated, the pump laser is tuned backwards to reduce the initial number of solitons down to a single one[30]. The schematics on the right show the corresponding intracavity waveforms in different states (modulation-instability, multiple-soliton and single-soliton states). **c**, Measured spectrum of a single-soliton frequency comb after suppression of residual pump light. The frequency comb features a smooth spectral envelope with a 3-dB bandwidth of 6 THz comprising hundreds of optical carriers extending beyond the telecommunication C and L bands (blue and red, respectively).

frequency shift of $g = \hbar\omega_0^2 c n_2/(n^2 V_{\mathrm{eff}})$, where n_2 (n) is the nonlinear (linear) refractive index, c the speed of light in vacuum, $\hbar$ the reduced Planck constant, V_{eff} the nonlinear optical mode volume and ω_0 the angular frequency of the pump mode. For pump powers that cause the Kerr frequency shift of the cavity to exceed the linewidth of the resonance, parametric oscillations lead to the formation of Kerr frequency combs (modulation-instability Kerr combs). Bright DKSs can be formed via this process when the microresonator is driven by a continuous-wave laser excitation with frequency ω_L that is red-detuned from the cavity resonance ($\delta\omega = \omega_0 - \omega_L > 0$) and has a locally anomalous group velocity dispersion (that is, the Taylor expansion for the angular frequency of the cavity modes $\omega_\mu = \omega_0 + \sum_{i=1}^{\infty} D_i \mu^i / i!$ has $D_2 > 0$, where μ is the relative mode index with respect to the pumped cavity mode and D_i are the dispersion terms). Mathematically, DKS states appear as specific solutions of the Lugiato–Lefever equation[22] (a driven, nonlinear Schrödinger equation that contains damping and detuning and was first used to describe spontaneous spatial pattern formation) and consist of an integer number of discrete hyperbolic-secant-shaped pulses on a continuous-wave background that circulate in the cavity[3]. The stability of such states relies on the double balance of dispersion and Kerr nonlinearity and of nonlinear parametric gain and cavity loss. Theoretically predicted[4] and reported[3] to spontaneously form in microresonators made from crystalline MgF_2, DKSs have been observed in different types of material systems including silica-on-silicon[23], silicon nitride[6] (Si_3N_4) and silicon[24]. Of particular interest are single-soliton states, which consist of only one ultrashort pulse circulating around the cavity, leading to a broadband comb spectrum with a smooth and numerically predictable[3] envelope given by

$$P(\mu) \approx \frac{\kappa_{\mathrm{ex}} D_2 \hbar \omega_0}{4g} \mathrm{sech}^2\left(\frac{\pi\mu}{2}\sqrt{\frac{D_2}{2\delta\omega}}\right)$$

where κ_{ex} represents the external coupling rate to the bus waveguide (see Supplementary Information for more details). DKSs have already been used in applications such as self-referencing of optical frequency combs[25,26], low-noise microwave generation[27] and dual soliton comb spectroscopy[24,28].

Our demonstration comprises a series of three experiments that exploit the extraordinarily smooth, broadband spectral envelope and the inherently low phase noise of DKS combs for massively parallel coherent communications. In the first experiment, we transmit data on 94 carriers that span the entire telecommunication C and L bands with a line spacing of about 100 GHz. Using 16-state quadrature amplitude modulation (16QAM) to encode data on each of the lines, we achieve an aggregate line rate of 30.1 Tbit s^{-1}. In the second experiment, we double the number of carriers by interleaving two DKS combs. This gives a total of 179 carriers and an aggregate line rate of 55.0 Tbit s^{-1} transmitted over a distance of 75 km—the highest data rate achieved

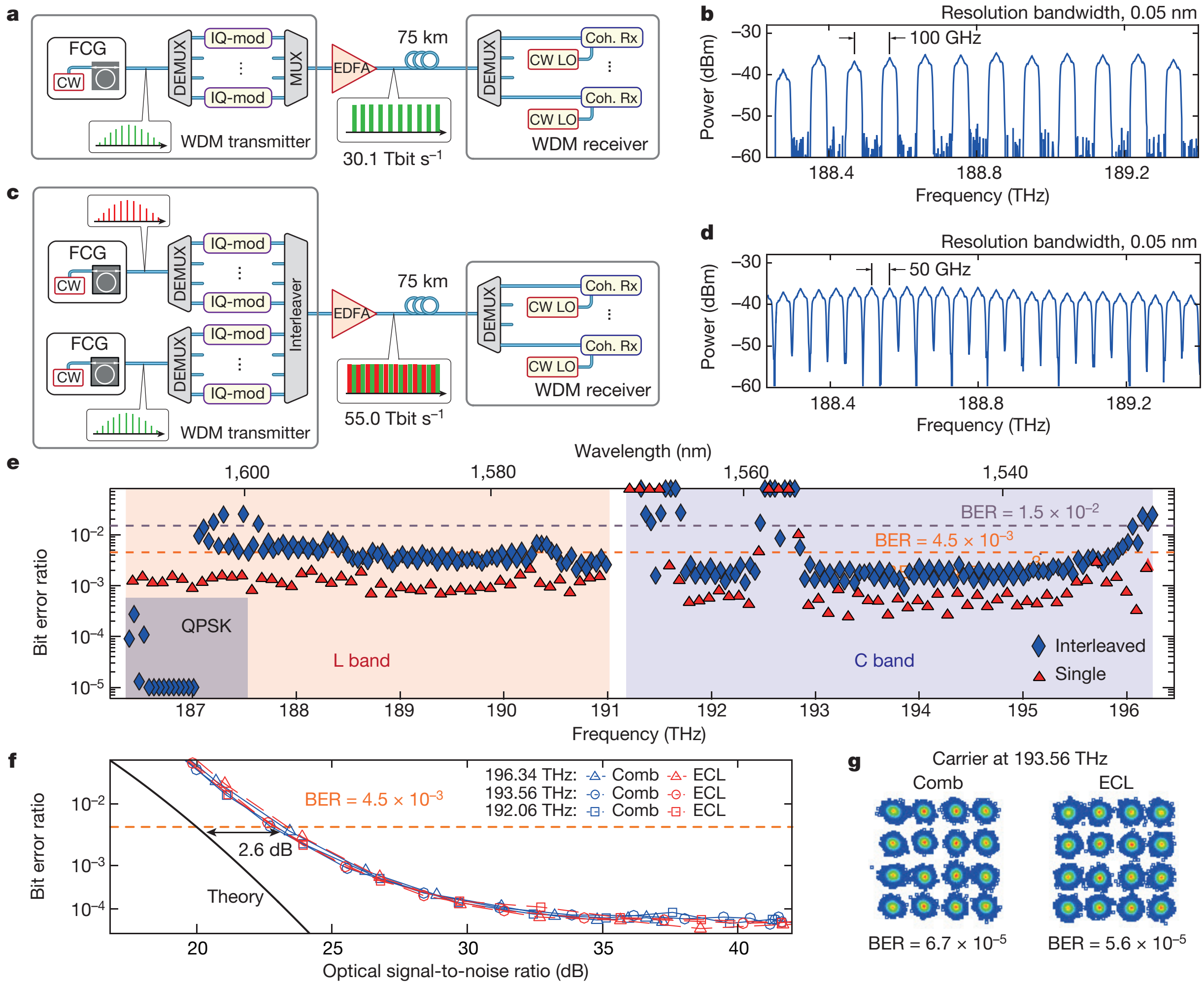

Figure 2 | Data transmission using microresonator dissipative Kerr-soliton combs for massively parallel WDM. a, Principle of data transmission using a single DKS comb generator as the optical source at the transmitter. A de-multiplexer (DEMUX) separates the comb lines and routes them to individual dual-polarization in-phase/quadrature modulators ('IQ-mod'), which encode independent data on each polarization. The data channels are then recombined into a single-mode fibre using a multiplexer (MUX) and boosted by an EDFA before being transmitted. At the receiver, the wavelength channels are separated by a second de-multiplexer and detected using digital coherent receivers ('Coh. Rx') along with individual continuous-wave lasers as local oscillators ('CW LO'). In our laboratory experiments, we emulate WDM transmission by independent modulation of even and odd carriers using two in-phase/quadrature modulators; see Supplementary Information section 2 for more details. We use 16QAM at a symbol rate of 40 GBd per channel. CW, continuous-wave laser; FCG, frequency comb generator. **b**, Section of the optical spectrum of the WDM data stream. Nyquist pulse shaping leads to approximately 40-GHz-wide rectangular power spectra for each of the carriers, which are spaced by approximately 100 GHz. **c**, Principle of data transmission using a pair of interleaved DKS combs at the transmitter. The resulting comb features a carrier spacing of approximately 50 GHz, which enables dense spectral packing of WDM channels and hence high spectral efficiency. At the receiver, this scheme still relies on individual continuous-wave lasers as local oscillators for coherent detection; see Supplementary Information section 2 for details. **d**, Section of the optical spectrum of the WDM data stream. **e**, Measured bit error ratios (BERs; 10^6 bits compared) of the transmitted channels for the single-comb (red triangles) and interleaved-comb (blue diamonds) experiments, along with the BER thresholds[31] for error-free propagation when applying FEC schemes with 7% overhead (4.5×10^{-3}, dashed orange line) and 20% overhead (1.5×10^{-2}, dashed blue line); see Methods for details. For the interleaved-comb experiment, the outer 14 lines at the low-frequency edge of the L band (purple shaded region) were modulated with quadrature phase-shift keying (QPSK) signals rather than 16QAM owing to the low optical signal-to-noise ratio of these carriers. **f**, Measured BER versus optical signal-to-noise ratio of three different channels, centred at frequencies of 196.34 THz, 193.56 THz and 192.06 THz, and derived from a DKS frequency comb (blue) and a high-quality ECL (red), all with 16QAM signalling at 40 GBd. A total of 10^6 bits were compared. The comb lines do not show any additional penalty compared to the ECL tones. The black solid line ('Theory') indicates the theoretical dependence of the BER on the optical signal-to-noise ratio for an ideal transmission system; see Supplementary Information, section 3. Similar results were obtained at other symbol rates, including 28 GBd, 32 GBd and 42.8 GBd. **g**, Constellation diagrams obtained for an ECL and DKS comb tone at a carrier frequency of 193.56 THz. The colour indicates the relative density of symbols detected in the complex plane, with red indicating a higher density and blue a lower density. The optical signal-to-noise ratio is approximately 35 dB.

so far with a chip-scale frequency comb source. In the third experiment, we demonstrate coherent detection using a DKS comb as a multi-wavelength local oscillator. We use 93 carriers to transmit and receive an aggregated line rate of 37.2 Tbit s^{-1}. In this experiment, the local-oscillator comb is coarsely synchronized to the transmitter comb, and digital signal processing is used to account for remaining frequency differences. The results demonstrate the potential of Kerr soliton combs, both as multi-wavelength optical sources and as local oscillators for massively parallel WDM transmission.

Our work relies on integrated Si_3N_4 microresonators[5,6] for generation of DKS frequency combs (Fig. 1a). The Si_3N_4 platform is chosen because of its low optical losses and its compatibility with large-scale silicon-based processing[5]. The microresonators have a waveguide height of 800 nm to achieve anomalous group velocity dispersion and

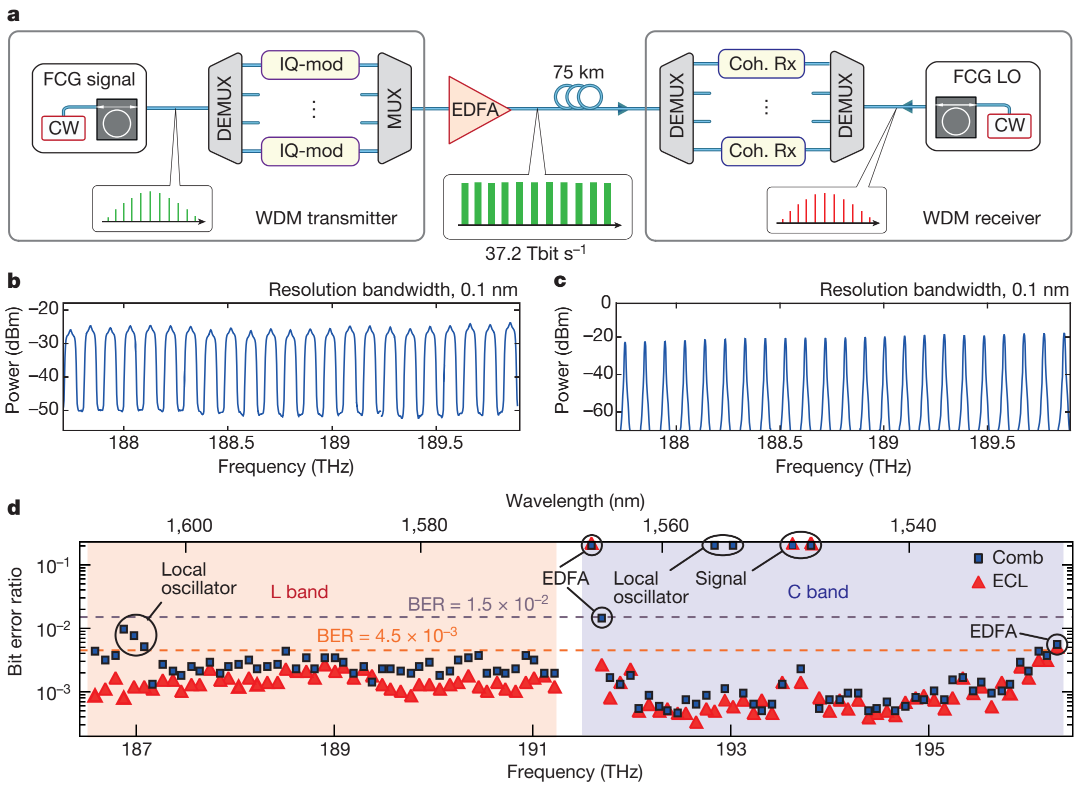

Figure 3 | Coherent data transmission using microresonator dissipative Kerr-soliton combs at both the transmitter and the receiver. a, Massively parallel WDM data transmission scheme using DKS frequency combs as both multi-wavelength source at the transmitter and multi-wavelength local oscillator (LO) at the receiver. In contrast to Fig. 2a, a single optical source provides all of the local-oscillator tones that are required for coherent detection. An extra de-multiplexer is used to route each local-oscillator tone to the respective coherent receiver. **b**, Section of the spectrum of the transmitted channels. **c**, Corresponding section of the spectrum of the local-oscillator frequency comb. Note that the comparatively large width of the depicted spectral lines is caused by the resolution bandwidth of the spectrometer (0.1 nm) and does not reflect the sub-100-kHz optical linewidth of the local-oscillator tones. **d**, Measured BERs for each data channel. Blue squares show the results obtained when using a DKS comb as the multi-wavelength local oscillator and red triangles correspond to a reference measurement using a high-quality ECL. Dashed lines mark the BER thresholds of 4.5×10^{-3} (1.5×10^{-2}) for hard-decision (soft-decision) FEC with 7% (20%) overhead. Black circles show the channels with BERs above the threshold for 7% FEC and specify the reasons for low signal quality: a low optical carrier-to-noise ratio of the carriers from the local-oscillator comb ('Local oscillator') and the signal comb ('Signal'), and bandwidth limitations of the C-band EDFA ('EDFA'); see Methods for more details.

are fabricated using the photonic Damascene process[29]. Neighbouring resonances are spaced by 100 GHz and have intrinsic quality (Q) factors exceeding 10^6. DKS combs are obtained by sweeping the pump laser through the resonance from a blue-detuned wavelength to a predefined red-detuned wavelength[3,6]. This leads initially to the generation of modulation-instability Kerr combs followed by DKS states once the resonance is crossed (Fig. 1). Importantly, once a multiple-soliton comb state is generated, the transition to a single-soliton state can be accomplished in a reliable and deterministic manner[30] by adjusting the laser frequency (Fig. 1a, b, Methods). The measured power spectrum of the DKS comb state is shown in Fig. 1c and exhibits a 3-dB spectral bandwidth of approximately 6 THz. The soliton comb states are remarkably stable for many hours in a laboratory environment, which is key to the transmission experiments presented here.

The general concept of massively parallel data transmission using a frequency comb as a multi-wavelength light source is depicted in Fig. 2a and demonstrated in the first transmission experiment. To emulate massively parallel WDM transmission in our laboratory, we rely on a simplified scheme that uses only two independent data streams on neighbouring channels along with an emulation of polarization division multiplexing; see Supplementary Information section 2 for details. We use 16QAM at a symbol rate of 40 gigabauds (GBd) along with band-limited Nyquist pulses that have approximately rectangular power spectra (Fig. 2b). At the receiver, each channel is individually characterized using a continuous-wave laser as the local oscillator along with an optical modulation analyser, which extracts signal quality parameters such as the error-vector magnitude and the bit error ratio (BER). The BERs of the first transmission experiment are depicted in Fig. 2e, with different BER thresholds indicated as horizontal dashed lines. For a given forward error correction (FEC) scheme, these thresholds define the maximum BER of the raw data channel that can still be corrected to a BER of less than 10^{-15}, which is considered error-free[31] (Methods). Of the 101 carriers derived from the comb in the C and L bands, 94 channels were used for data transmission, resulting in a total line rate of 30.1 Tbit s^{-1}; see Methods for details on data rate calculations. In our experiment, the transmission capacity is restricted by the fact that the line spacing of about 100 GHz substantially exceeds the signal bandwidth of about 40 GHz, leading to unused frequency bands between neighbouring channels (Fig. 2b) and hence to a rather low spectral efficiency of 2.8 bit s^{-1} Hz^{-1}.

These restrictions can be overcome by using interleaved frequency combs (Fig. 2c), as demonstrated in the second transmission experiment. This scheme uses a pair of DKS combs with practically identical line spacing, which are shifted with respect to each other by half the line spacing (Methods). At the receiver, this scheme still relies on individual continuous-wave lasers as local oscillators for coherent detection. The interleaved comb features a line spacing of about 50 GHz, which enables dense packing of 40-GBd data channels in the spectrum (Fig. 2d). The BER results of the second transmission experiment are depicted in Fig. 2e. We find a total of 204 tones in the C and L bands, of which 179 carriers could be used for data transmission. The remaining channels were not usable owing to technical limitations (Supplementary

Information section 2). The transmission performance is slightly worse than in the single-comb experiment because twice the number of carriers had to be amplified by the same erbium-doped fibre amplifiers (EDFA), which were operated at their saturation output power such that the power per data channel reduced accordingly. Nevertheless, data was successfully transmitted over 75 km of standard single-mode fibre at a symbol rate of 40 GBd using a combination of 16QAM and quadrature phase-shift keying. The total line rate amounts to 55.0 Tbit s^{-1} and the net data rate is 50.2 Tbit s^{-1}, see Methods for details on data rate calculations. This data rate is the highest achieved so far with a chip-scale frequency comb source and compares very well to the highest capacity of 102.3 Tbit s^{-1} ever shown for a single-mode fibre core[32] using more than 200 discrete distributed feedback lasers as optical sources at the transmitter. In addition, we achieve an unprecedented spectral efficiency of 5.2 bit s^{-1} Hz^{-1} as a result of the densely packed spectrum (Fig. 2d). In the experiments, the limited saturation output power of the EDFA that we used is the main constraint of signal quality and BER; see Supplementary Information sections 2 and 5.3 for details. The data rates we present are hence not limited by the DKS comb source, but by the components of the current transmission set-up, leaving room for further improvement.

To exemplify the potential of DKS combs for data transmission, we compare the transmission performance of a single-comb line to that of a reference carrier derived from a high-quality benchtop-type external-cavity laser (ECL) with an optical linewidth of approximately 10 kHz, an optical output power of 15 decibels relative to 1 mW (dBm) and an optical carrier-to-noise ratio in excess of 60 dB. As a metric for the comparison, we use the optical signal-to-noise ratio penalty at a BER of 4.5×10^{-3}, which corresponds to the threshold for FEC with 7% overhead[31]. The results for 40-GBd 16QAM transmission are shown in Fig. 2f for three different comb lines and for ECL reference transmission experiments at the corresponding comb line frequencies. The optical signal-to-noise ratios are defined for a reference bandwidth of 0.1 nm (Supplementary Information section 3). As shown, no additional penalty is observed for the frequency comb when compared with the high-quality ECL: for both sources, we observe an optical signal-to-noise ratio penalty of 2.6 dB with respect to the theoretically required value (black line in Fig. 2f) for a BER of 4.5×10^{-3}. DKS-based light sources can therefore markedly improve the scalability of WDM systems without impairing the signal quality under realistic transmission conditions. The error floor in Fig. 2f is attributed to transmitter nonlinearities and electronic receiver noise in our set-up. In Fig. 2g we show the measured constellation diagrams for the ECL and the comb line at 193.56 THz, both taken at the same optical signal-to-noise ratio of 35 dB.

To demonstrate the potential of DKS frequency combs as multi-wavelength local oscillators at the receiver, we perform a third experiment, shown schematically in Fig. 3a. At the transmitter, a first DKS comb source with a free spectral range of about 100 GHz serves as an optical source. At the receiver, a second DKS comb generator with approximately the same free spectral range is used to generate the corresponding local-oscillator tones, each featuring an optical linewidth of less than 100 kHz. In Fig. 3b, c we show a section of the transmitted data spectrum along with the corresponding section of the local-oscillator comb. As a reference, the same experiment was repeated using a high-quality ECL with a 10-kHz linewidth as a local oscillator for channel-by-channel demodulation. Overall, an aggregate line rate of 37.2 Tbit s^{-1} is obtained (Methods). The resulting BERs of all 99 channels for both methods are shown in Fig. 3d. Some of the channels showed signal impairments due to limitations of the available equipment (Methods); however, we did not observe any considerable penalty that could be systematically attributed to using the DKS comb as a local oscillator.

As well as offering fundamental technical advantages compared to discrete lasers, frequency combs can also reduce the power consumption of the transmission system. In this context, the power conversion efficiency of the DKS comb source is an important metric, defined as the ratio between the power of the pump and that of the generated comb lines. The power conversion efficiency of our comb sources is limited to rather small values of 0.1%–0.6% owing to the fundamental principle that bright-soliton generation occurs only with the pump laser being far-detuned from the optical resonance[3]. Nevertheless, the overall power consumption of comb sources can already compete with massively parallel arrays of commercially available integrated tunable laser assemblies; see Methods and Supplementary Information section 5 for details. The analysis also shows that an improvement of more than one order of magnitude compared to integrated tunable laser assemblies is possible by optimizing the microresonator dispersion, by making use of tailored amplifiers with optimum efficiency, and by increasing the power conversion efficiency by using high-Q Si_3N_4 microresonators with Q factors of 6×10^6.

In summary, we have demonstrated the potential of chip-scale DKS frequency combs for massively parallel WDM at data rates of tens of terabits per second. We use them as both multi-wavelength sources at the transmitter and multi-wavelength local oscillators at the receiver, and we show in both cases that that there is no systematic penalty compared to using high-quality ECL. Although our experiments achieve the highest data rate with chip-scale frequency comb sources so far, there is still room for increasing the transmission capacity by optimizing the transmitter or by using the adjacent S and U bands for data transmission in the near-infrared. For long transmission distances, comb-based transmission schemes might compensate nonlinear impairments and hence lead to an improved signal quality compared to conventional WDM schemes[13]. The results demonstrate the potential of DKS comb sources for high-speed data transmission, both in petabit-per-second intra-datacentre networks and in inter-datacentre connections.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 10 August 2016; accepted 18 April 2017.

1. Hasegawa, A. & Kodama, Y. *Solitons in Optical Communications* (Clarendon Press, 1995).
2. Mollenauer, L. F., Stolen, R. H. & Gordon, J. P. Experimental observation of picosecond pulse narrowing and solitons in optical fibers. *Phys. Rev. Lett.* **45,** 1095–1098 (1980).
3. Herr, T. *et al.* Temporal solitons in optical microresonators. *Nat. Photon.* **8,** 145–152 (2014).
4. Akhmediev, N. & Ankiewicz, A. *Dissipative Solitons: From Optics to Biology and Medicine* (Springer, 2008).
5. Levy, J. S. *et al.* CMOS-compatible multiple-wavelength oscillator for on-chip optical interconnects. *Nat. Photon.* **4,** 37–40 (2010).
6. Brasch, V. *et al.* Photonic chip-based optical frequency comb using soliton Cherenkov radiation. *Science* **351,** 357–360 (2016).
7. Bozinovic, N. *et al.* Terabit-scale orbital angular momentum mode division multiplexing in fibers. *Science* **340,** 1545–1548 (2013).
8. Puttnam, B. J. *et al.* 2.15 Pb/s transmission using a 22 core homogeneous singlemode multi-core fiber and wideband optical comb. In *European Conference on Optical Communication* PDP3.1 (ECOC, 2015).
9. Dai, D. & Bowers, J. E. Silicon-based on-chip multiplexing technologies and devices for peta-bit optical interconnects. *Nanophotonics* **3,** 283–311 (2014).
10. Nakazawa, M., Yamada, E., Kubota, H. & Suzuki, K. 10 Gbit/s soliton data transmission over one million kilometres. *Electron. Lett.* **27,** 1270–1272 (1991).
11. Ataie, V. *et al.* Ultrahigh count coherent WDM channels transmission using optical parametric comb based frequency synthesizer. *J. Lightwave Technol.* **33,** 694–699 (2015).
12. Hillerkuss, D. *et al.* Single-laser 32.5 Tbit/s Nyquist WDM transmission. *J. Opt. Commun. Netw.* **4,** 715–723 (2012).
13. Temprana, E. *et al.* Overcoming Kerr-induced capacity limit in optical fiber transmission. *Science* **348,** 1445–1448 (2015).
14. Weimann, C. *et al.* Silicon-organic hybrid (SOH) frequency comb sources for terabit/s data transmission. *Opt. Express* **22,** 3629–3637 (2014).
15. Pfeifle, J. *et al.* Flexible terabit/s Nyquist-WDM super-channels using a gain-switched comb source. *Opt. Express* **23,** 724–738 (2015).
16. Kemal, J. *et al.* 32QAM WDM transmission using a quantum-dash passively mode-locked laser with resonant feedback. In *Optical Fiber Communication Conference* Th5C.3 (Optical Society of America, 2017).

17. Hu, H. *et al.* Single-source AlGaAs frequency comb transmitter for 661 Tbit/s data transmission in a 30-core fiber. In *Conference on Lasers and Electro-Optics* JTh4C.1 (Optical Society of America, 2016).
18. Kemal, J. N. *et al.* Multi-wavelength coherent transmission using an optical frequency comb as a local oscillator. *Opt. Express* **24,** 25432–25445 (2016).
19. Del'Haye, P. *et al.* Optical frequency comb generation from a monolithic microresonator. *Nature* **450,** 1214–1217 (2007).
20. Kippenberg, T. J., Holzwarth, R. & Diddams, S. A. Microresonator-based optical frequency combs. *Science* **332,** 555–559 (2011).
21. Pfeifle, J. *et al.* Coherent terabit communications with microresonator Kerr frequency combs. *Nat. Photon.* **8,** 375–380 (2014).
22. Lugiato, L. A. & Lefever, R. Spatial dissipative structures in passive optical systems. *Phys. Rev. Lett.* **58,** 2209–2211 (1987).
23. Yi, X., Yang, Q.-F., Yang, K. Y., Suh, M.-G. & Vahala, K. Soliton frequency comb at microwave rates in a high-*Q* silica microresonator. *Optica* **2,** 1078–1085 (2015).
24. Yu, M. *et al.* Silicon-chip-based mid-infrared dual-comb spectroscopy. Preprint at https://arxiv.org/abs/1610.01121 (2016).
25. Jost, J. *et al.* Counting the cycles of light using a self-referenced optical microresonator. *Optica* **2,** 706–711 (2015).
26. Brasch, V., Lucas, E., Jost, J. D., Geiselmann, M. & Kippenberg, T. J. Self-referenced photonic chip soliton Kerr frequency comb. *Light Sci. Appl.* **6,** e16202 (2017).
27. Liang, W. *et al.* High spectral purity Kerr frequency comb radio frequency photonic oscillator. *Nat. Commun.* **6,** 7957 (2015).
28. Suh, M.-G., Yang, Q.-F., Yang, K. Y., Yi, X. & Vahala, K. J. Microresonator soliton dual-comb spectroscopy. *Science* **354,** 600–603 (2016).
29. Pfeiffer, M. H. P. *et al.* Photonic Damascene process for integrated high-*Q* microresonator based nonlinear photonics. *Optica* **3,** 20–25 (2016).
30. Guo, H. *et al.* Universal dynamics and deterministic switching of dissipative Kerr solitons in optical microresonators. *Nat. Phys.* **13,** 94–102 (2017).
31. Chang, F., Onohara, K. & Mizuochi, T. Forward error correction for 100 G transport networks. *IEEE Commun. Mag.* **48,** S48–S55 (2010).
32. Sano, A. *et al.* 102.3-Tb/s (224 × 548-Gb/s) C- and extended L-band all-Raman transmission over 240 km using PDM-64QAM single carrier FDM with digital pilot tone. In *Optical Fiber Communication Conference* PDP5C.3 (Optical Society of America, 2012).
33. Kordts, A., Pfeiffer, M., Guo, H., Brasch, V. & Kippenberg, T. J. Higher order mode suppression in high-*Q* anomalous dispersion SiN microresonators for temporal dissipative Kerr soliton formation. *Opt. Lett.* **41,** 452–455 (2016).

Supplementary Information is available in the online version of the paper.

Acknowledgements This work was supported by the European Research Council (ERC Starting Grant 'EnTeraPIC', number 280145), the EU project BigPipes, the Alfried Krupp von Bohlen und Halbach Foundation, the Karlsruhe School of Optics and Photonics (KSOP), and the Helmholtz International Research School for Teratronics (HIRST). P.M.-P. is supported by the Erasmus Mundus doctorate programme Europhotonics (grant number 159224-1-2009-1-FR-ERA MUNDUS-EMJD). We acknowledge financial support by the Deutsche Forschungsgemeinschaft (DFG) through the Collaborative Research Center 'Wave Phenomena: Analysis and Numerics' (CRC 1173), project B3 'Frequency combs'. Si_3N_4 devices were fabricated and grown in the Center of MicroNanoTechnology (CMi) at EPFL. EPFL acknowledges support by an ESA PhD fellowship (M.K.) and by the Air Force Office of Scientific Research, Air Force Material Command, USAF, number FA9550-15-1-0099. M.K. acknowledges funding support from Marie Curie FP7 ITN FACT. We also acknowledge the Swiss National Science Foundation via precoR, Grant No. 161537. This publication was supported by Contract W911NF-11-1-0202 (QuASAR) from the Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office (DSO).

Author Contributions P.M.-P., J.N.K. and J.P. built the system for data transmission, supervised by C.K. A.K. and M.H.P.P. designed and fabricated the Si_3N_4 microresonators, supervised by T.J.K. P.M.-P., M.K. and A.K. characterized and selected the samples. M.K., V.B., A.K. and M.H.P.P. developed the soliton generation technique, supervised by T.J.K. J.P., P. M.-P. and K.V. performed the OSNR characterization of the optical source. P.M.-P., J.P., P.T., S.W., J.N.K., K.V. and R.R. carried out the data transmission experiments, supervised by C.K. M.K. and M.H.A. theoretically investigated the optimization of the power conversion efficiency of DKS sources. The project was initiated and supervised by W.F., T.J.K. and C.K. All authors discussed the data. The manuscript was written by P.M.-P., J.N.K., M.K., T.J.K. and C.K.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare competing financial interests: details are available in the online version of the paper. Readers are welcome to comment on the online version of the paper. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to C.K. (christian.koos@kit.edu) or T.J.K. (tobias.kippenberg@epfl.ch).

Reviewer Information *Nature* thanks V. Torres-Company and the other anonymous reviewer(s) for their contribution to the peer review of this work.

METHODS

High-*Q* Si_3N_4 microresonators. We use Si_3N_4 microresonators to generate DKS frequency combs. These devices lend themselves to co-integration with other photonic devices, using either monolithic approaches on silicon[9] or indium phosphide (InP)[34], hybrid InP-on-silicon approaches[35], or multi-chip concepts[15,36]. A particularly attractive option is to co-integrate DKS comb sources with advanced multiplexer and de-multiplexer circuits[9] and with highly power-efficient in-phase/quadrature modulators[37,38] to realize chip-scale transceivers that can handle tens of terabits per second of data traffic, as already envisioned in ref. 15. For soliton formation, anomalous group velocity dispersion is required, necessitating Si_3N_4 waveguide heights of approximately 800 nm for a width of 1.65 μm. These dimensions are achieved by using the photonic Damascence process[29], along with a waveguide filtering section to achieve an undistorted dispersion profile[33]. The mode-filtering section suppresses higher-order modes[33] (Fig. 1a inset) and so minimizes the number of avoided-mode crossings and facilitates soliton comb generation.

Fabrication reproducibility was investigated, exhibiting a yield of chips that enable DKS generation of approximately 40%. For different microresonators taken from the same wafer, we measured an average line spacing of 95.75 GHz with a standard deviation of approximately 70 MHz. We attribute such differences to variations in both the width of the waveguide and the thickness of the Si_3N_4 layer between distant microresonators within the same wafer. These variations are approximately 20 nm and may be reduced by increasing the uniformity of the fabrication process over the entire wafer. In particular, we expect that the use of highly developed large-scale fabrication equipment such as 193-nm deep-ultraviolet lithography and thin-film tools with improved uniformity will overcome these shortcomings in device reproducibility, as already demonstrated in the context of silicon photonics[39]. The line spacing difference between frequency combs can be compensated through thermal tuning, which allows us to adapt the free spectral range of the microresonators over a tuning range of more than 40 MHz, with a precision of approximately 200 kHz. The same technique can be applied to precisely match the line spacing to established International Telecommunications Union (ITU) grids.

In addition, we measured the power conversion efficiency of the DKS comb sources used in our experiment, yielding values that range from 0.1% to 0.6%. The differences are attributed to variations in the quality factors of the pumped resonances, which may be caused by interactions of the fundamental mode with higher-order modes. Even though mode-filtering sections are used to suppress the propagation of higher-order modes within the waveguide, we still observe slight variations in the spectral envelope with respect to the theoretical $\text{sech}^2(x)$ shape. These variations are indicative of the presence of avoided-mode crossings, which are characteristic of multimode waveguides. We expect that these limitations can be overcome by optimized device design.

For DKS comb sources with improved power efficiency, high *Q* factors are of great importance. Si_3N_4 resonators have been demonstrated[40,41] with *Q* factors of more than 6×10^6 both in devices with normal[40] and anomalous[41] group velocity dispersions. Along with tailored optical amplifiers, such devices enable the electrical power consumption to be reduced by more than an order of magnitude compared to state-of-the-art integrated tunable laser assemblies (Supplementary Information section 5.1).

Soliton comb generation. The DKS combs are generated by pumping the microresonators with an ECL and a subsequent EDFA, which is operated at an output power of approximately 35 dBm; see Supplementary Information section 1 and Supplementary Fig. 1 for a more detailed description of the comb generation set-up. A high-power band-pass filter with a 3-dB bandwidth of 0.8 nm is used to suppress the amplified stimulated emission (ASE) noise that originates from the pump amplifier. The soliton state is excited by well-controlled wavelength tuning[3] of the pump ECL from low to high wavelengths across the resonance at a rate of approximately 100 pm s^{-1}. Once a multiple-soliton state is obtained, the transition to a single-soliton state is accomplished by fine-tuning the pump laser towards lower wavelengths[30]. This slow sweep is performed at a rate of approximately 1 pm s^{-1}. Light is coupled into and out of the on-chip Si_3N_4 waveguides using lensed fibres, which have spot size diameter of 3.5 μm and coupling losses of 1.4 dB per facet. The pump power in the on-chip waveguide amounts to approximately 32 dBm. The frequency comb used in the single-comb transmission experiment has a line spacing of 95.80 GHz and a 3-dB bandwidth of more than 6 THz. The optical linewidth of individual comb carriers is limited by the optical linewidth of our tunable pump lasers (TLB-6700, New Focus and TSL-220, Santec), which is less than 100 kHz. This value is well below that of telecommunication-grade distributed feedback lasers[42] and so is perfectly suited for coherent data transmission[43]. No additional linewidth broadening relative to the pump is measured; that is, the phase noise of the comb lines is entirely dominated by the pump.

An alternative approach to DKS generation has recently been demonstrated[44], whereby the detuning of the pump laser with respect to the resonance is adjusted by thermally shifting the resonance using integrated heaters rather than by tuning the wavelength of the pump laser. This technique enables the tunable pump lasers to be replaced by much more stable continuous-wave pump lasers with sub-kilohertz linewidths.

At the output of the microresonator, a tunable fibre Bragg grating acts as a notch filter to suppress residual pump light to a power level that matches the other comb carriers. After the fibre Bragg grating, the measured optical power of the entire comb spectrum (Fig. 1c) amounts to 4 dBm. For the experiments using interleaved transmitter frequency combs or a separate receiver local-oscillator comb, a second DKS comb source with similar performance is used. The frequency comb from the second device for the interleaved transmitter combs (receiver local oscillator) features a slightly different line spacing of 95.82 GHz (95.70 GHz) and overall optical power of 0 dBm (8 dBm). For the transmission experiments, an EDFA is used to amplify the combs to an approximate power of 5 dBm per line before modulation. The carriers next to the pumped resonance are superimposed by strong ASE noise that originates from the optical amplifier. In future implementations, impairment by ASE noise can be greatly reduced by extracting the comb light from the microresonator using a drop-port geometry[45]. This approach would avoid direct transmission of broadband ASE noise through the device and would render the notch filter for pump light suppression superfluous.

DKS comb tuning and interleaving. Precise interleaving of the frequency combs in the second transmission experiment is achieved by adjusting the temperature of each microresonator, thereby changing the refractive index and shifting the resonance frequencies while leaving the free spectral range essentially unchanged[46]. A detailed sketch of the experimental set-up is given in Supplementary Information section 1. The resonance frequencies of the cavity can be tuned at a rate of approximately -2.5 GHz K^{-1} with an accuracy of approximately 200 MHz, limited by the resolution of the temperature controller of approximately 0.1 K. In addition, as a consequence of intra-pulse Raman scattering[47], the centre frequency of the comb can be tuned by slowly changing the pump frequency during operation at a constant external temperature. The associated tuning range is limited to approximately $\pm$500 MHz before the comb state is lost; the tuning resolution is given by the pump laser and amounts to approximately 10 MHz for our devices (TLB-6700, New Focus; TSL-220, Santec). These tuning procedures are used both for precise interleaving of DKS combs in the second transmission experiment and for synchronizing the local-oscillator comb to the transmitter comb in the third transmission experiment.

Data transmission experiments. For the data transmission experiments[48–50], the single or interleaved frequency comb is amplified to 26.5 dBm by a C/L-band EDFA, before the lines are equalized and de-interleaved into 'odd' and 'even' carriers to emulate WDM. In the laboratory experiment, the de-multiplexer depicted in Fig. 2a is implemented by two programmable filters (Finisar WaveShaper) along with C- and L-band filters, which act as de-interleavers to separate the combs into two sets of even and odd carriers; see Supplementary Information section 2 for a more detailed description of the experimental set-up. After separation, the carriers are routed to individual in-phase/quadrature modulators, which encode independent data streams on each set of carriers using both the amplitude and the phase of the optical signal as carriers of information. To this end, we use two optical in-phase/quadrature modulators, which are driven by pseudo-random bit sequences with lengths of $2^{11}-1$ using quadrature phase-shift keying or 16QAM signalling and raised-cosine pulse shaping with a roll-off factor of $\beta = 0.1$. The drive signals were generated by arbitrary-waveform generators. For the transmission experiment using frequency combs as the optical source at the transmitter, the symbol rate was 40 GBd and the sampling rate of the arbitrary-waveform generator (Keysight M8195A) was 65 gigasamples (GSa) per second. For the experiment with a DKS comb as a multi-wavelength local oscillator, symbol rates of 50 GBd and sampling rates of 92 GSa s^{-1} (Keysight M8196A) were used. We refrained from using higher symbol rates because the limited electrical bandwidth of our transmitter and receiver hardware would have led to much worse signal quality. In all of the experiments, polarization division multiplexing (PDM) is emulated by a split-and-combine method, whereby the data stream of one polarization is delayed by approximately 240 bits with respect to the other to generate uncorrelated data[51]. The data channels are then recombined into a 75-km-long standard single-mode fibre by a multiplexer and boosted by an EDFA, before being transmitted. At the receiver, we select each channel individually using a band-pass filter with a 0.6-nm passband, followed by a C- or L-band EDFA and then another band-pass filter with a 1.5-nm passband. The signal is received and processed using an optical modulation analyser (Keysight N4391A) that relies on either a high-quality ECL line or a tone of another DKS comb as the local oscillator. In the latter case, we use an optical band-pass filter to extract the tone of interest from the local-oscillator comb; see Supplementary Information section 4 for details. In all of the experiments, we perform offline processing including filtering, frequency-offset compensation, clock recovery, polarization de-multiplexing, dispersion compensation and equalization.

Transmission impairments and data rates. In our transmission experiments, performance was impaired by specific limitations of the available laboratory equipment, which can be avoided in real-world transmission systems. For the transmission experiment using a single DKS comb generator as the optical source (Fig. 2a), 101 tones were derived from the comb in the C and L bands. Of those, 92 carriers performed better than the BER threshold of 4.5×10^{-3} for widely used second-generation FEC with 7% overhead[31] (Fig. 2e). The pump tone at approximately 192.66 THz and two neighbouring carriers could not be used for data transmission owing to strong ASE background from the pump EDFA. Two more directly adjacent channels exceeded the threshold of 4.5×10^{-3}, but were still below the BER threshold of 1.5×10^{-2} for soft-decision FEC with 20% overhead[31]. Another four channels at the low-frequency end of the C band were lost owing to a mismatch of the transmission band of the C-band filters that were used to realize the de-multiplexer; see Supplementary Information section 2 for a more detailed description. This leads to an overall net data rate (line rate) of 28.0 Tbit s^{-1} (30.1 Tbit s^{-1}).

For the transmission experiment using interleaved DKS combs as the optical source at the transmitter (Fig. 2c), we use a combination of 16QAM and quadrature phase-shift keying, depending on the optical signal-to-noise ratio (OSNR) of the respective carrier (Fig. 2e). For 16QAM transmission, 126 channels have a BER of less than 4.5×10^{-3}, requiring an FEC overhead of 7%, and 39 additional channels had a BER below 1.5×10^{-2}, which can be corrected by FEC schemes with 20% overhead. For the 14 channels at the low-frequency edge of the L band, the modulation format was changed to quadrature phase-shift keying owing to the low power of those carriers, which is caused by a decrease in the amplification of the L-band EDFA in this wavelength range. This leads to an overall net data rate (line rate) of 50.2 Tbit s^{-1} (55.0 Tbit s^{-1}).

For the transmission experiment using DKS frequency combs at both the transmitter and the receiver side (Fig. 3a), 99 tones were transmitted and tested. Of those, 89 channels perform better than the BER threshold for hard-decision FEC with 7% overhead (4.5×10^{-3}) and an additional 4 channels are below the BER limit of 1.5×10^{-2} for soft-decision FEC with 20% overhead. For the remaining channels, coherent reception was inhibited by low OSNR. This leads to an overall net data rate (line rate) of 34.6 Tbit s^{-1} (37.2 Tbit s^{-1}). The black circles in Fig. 3d show the channels with BERs above the threshold for 7% FEC and specify the reasons for low signal quality: low optical carrier-to-noise ratio (OCNR) of the carriers from the local-oscillator comb and the signal comb, or bandwidth limitations of the C-band EDFA.

Field-deployed WDM systems rely on statistically independent data channels rather than on transmitting identical data streams on the even and odd channels. As a consequence, real-world signals will suffer much less from coherent addition of nonlinear interference noise than the signals used in our experiments[52]. With respect to nonlinear impairments, our experiments therefore represent a worst-case scenario.

Characterization of the OSNR penalty of the frequency comb source. To compare the transmission performance of a single comb line to that of a high-quality ECL (Keysight N7714A) reference carrier, we measure the OSNR penalty at a BER of 4.5×10^{-3}, which corresponds to the threshold for FEC with 7% overhead[31]. For a given BER, the OSNR penalty is given by the decibel value of the ratio of the OSNR that was actually required to the OSNR that would theoretically be required in an ideal transmission set-up[53]. A detailed description of the associated experimental set-up is given in Supplementary Information section 3. The carrier under test is selected by a band-pass filter with a 1.3-nm-wide (160 GHz) passband. The carrier is then amplified to 24 dBm by an EDFA (EFDA2 in Supplementary Fig. 3) and modulated with a PDM 16QAM signal at 40 GBd. Next, an ASE noise source together with two variable optical attenuators are used to set the OSNR of the channel while keeping its optical power constant. As an ASE generator, we use a second EDFA (EDFA3 in Supplementary Fig. 3a). An optical spectrum analyser (Ando AQ6317B) is used to measure the OSNR at the input of the receiver. For each OSNR value, the quality of the channels is determined by measuring the BER using our previously described receiver configuration (Methods section 'Data transmission experiments'). At a BER of 4.5×10^{-3}, a penalty of 2.6 dB with respect to the theoretical OSNR value is observed (Fig. 2f), which is a common value for technical implementations of optical 16QAM transmitters[54]. For high OSNR, an error floor caused by transmitter nonlinearities and electronic receiver noise is reached. The maximum achievable OSNR of 44 dB at 192.56 THz for transmission with the comb line is dictated by ASE noise of the C/L-band EDFA (EDFA1) right after the frequency comb source (Supplementary Fig. 3). As a reference, the same measurements are repeated using a high-quality ECL (Keysight N7714A) to generate the carrier, which leads to essentially the same OSNR penalty for a given BER as the transmission with the comb line. For a symbol rate of 40 GBd, the results are shown in Fig. 2f; similar results are obtained at other symbol rates, including 28 GBd, 32 GBd and 42.8 GBd. For transmission with the ECL, only one EDFA (EDFA2) is needed to increase the power to 24 dBm before modulation. As a consequence, a higher maximum OSNR can be achieved with the ECL (58 dB) than with the comb line. For transmission with a single line, the lowest BER reached at 40 GBd is below 10^{-4} (Fig. 2f). However, this value is not reached in the WDM transmission experiment with the full comb (Figs 2a and 3d). For WDM transmission, a larger number of carriers are amplified by the EDFA in front of the modulator, which, together with the limited output power of the EDFA (EDFA2–5 in Supplementary Fig. 2a), decreases the optical power per line and hence the OCNR. Moreover, when interleaving two frequency combs, a variable optical attenuator and a directional coupler are inserted into the set-up, thereby introducing additional loss that needs to be compensated by the subsequent EDFA. Using additional EDFAs would therefore increase the quality of the signal that is received.

Data availability. Source Data for Figs 1c, 2b, d–f and 3b–d are provided with online version of the paper. The extended source data for Fig. 1b and the source data for the Supplementary Figures are provided as Supplementary Information. All other data supporting the findings of this study are available from the corresponding author on request.

34. Nagarajan, R. *et al.* InP photonic integrated circuits. *IEEE J. Sel. Top. Quant.* **16,** 1113–1125 (2010).
35. Liang, D. & Bowers, J. E. Recent progress in lasers on silicon. *Nat. Photon.* **4,** 511–517 (2010).
36. Lindenmann, N. *et al.* Photonic wire bonding: a novel concept for chip-scale interconnects. *Opt. Express* **20,** 17667–17677 (2012).
37. Lauermann, M. *et al.* 40 GBd 16QAM Signaling at 160 Gbit/s in a Silicon-Organic Hybrid (SOH) Modulator. *J. Lightw. Technol.* **33,** 1210–1216 (2015).
38. Koos, C. *et al.* Silicon-organic hybrid (SOH) and plasmonic-organic hybrid (POH) integration. *J. Lightwave Technol.* **34,** 256–268 (2016).
39. Selvaraja, S. K. *et al.* Fabrication of photonic wire and crystal circuits in silicon-on-insulator using 193-nm optical lithography. *J. Lightwave Technol.* **27,** 4076–4083 (2009).
40. Xuan, Y. *et al.* High-*Q* silicon nitride microresonators exhibiting low-power frequency comb initiation. *Optica* **3,** 1171–1180 (2016).
41. Pfeiffer, M. H. P. *et al.* Coupling ideality of integrated planar high-*Q* microresonators. *Phys. Rev. Appl*. **7,** 024026 (2017).
42. Puttnam, B. J. *et al.* High-capacity self-homodyne PDM-WDM-SDM transmission in a 19-core fiber. *Opt. Express* **22,** 21185–21191 (2014).
43. Pfau, T., Hoffmann, S. & Noe, R. Hardware-efficient coherent digital receiver concept with feedforward carrier recovery for M-QAM constellations. *J. Lightwave Technol.* **27,** 989–999 (2009).
44. Joshi, C. *et al.* Thermally controlled comb generation and soliton modelocking in microresonators. *Opt. Lett.* **41,** 2565–2568 (2016).
45. Wang, P.-H. *et al.* Intracavity characterization of micro-comb generation in the single soliton regime. *Opt. Express* **24,** 10890–10897 (2016).
46. Carmon, T., Yang, L. & Vahala, K. Dynamical thermal behavior and thermal self stability of microcavities. *Opt. Express* **12,** 4742–4750 (2004).
47. Karpov, M. *et al.* Raman self-frequency shift of dissipative Kerr solitons in an optical microresonator. *Phys. Rev. Lett.* **116,** 103902 (2016).
48. Pfeifle, J. *et al.* Full C and L-band transmission at 20 Tbit/s using cavity-soliton Kerr frequency combs. In *Conference on Lasers and Electro-optics* JTh5C.8 (Optical Society of America, 2015).
49. Marin, P. *et al.* 50 Tbit/s Massively parallel WDM transmission in C and L band using interleaved cavity-soliton Kerr combs. In *Conference on Lasers and Electro-optics* STu1G.1 (Optical Society of America, 2016).
50. Marin, P. *et al.* 34.6 Tbit/s WDM transmission using soliton Kerr frequency combs as optical source and local oscillator. In *European Conference on Optical Communication* PDP3.1 (ECOC, 2016).
51. Hillerkuss, D. *et al.* 26 Tbit s^{-1} line-rate super-channel transmission utilizing all-optical fast Fourier transform processing. *Nat. Photon.* **5,** 364–371 (2011).
52. Dar, R. *et al.* Impact of WDM channel correlations on nonlinear transmission. *In European Conference on Optical Communication* W.1.D.2 (ECOC, 2016)
53. Schmogrow, R. *et al.* Error vector magnitude as a performance measure for advanced modulation formats. *IEEE Photonics Technol. Lett.* **24,** 61–63 (2012).
54. Winzer, P. J., Gnauck, A. H., Doerr, C. R., Magarini, M. & Buhl, L. L. Spectrally efficient long-haul optical networking using 112-Gb/s polarization-multiplexed 16-QAM. *J. Lightwave Technol.* **28,** 547–556 (2010).