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Optical fibre communication is the backbone of the internet. As essential core technologies are approaching their limits of size, speed and energy-efficiency, there is a need for new technologies that offer further scaling of data transmission capacity. Here we show that a single optical frequency-comb source based on a silicon nitride ring resonator supports data capacities in the petabit-per-second regime. We experimentally demonstrate transmission of 1.84 Pbit s⁻¹ over a 37-core, 7.9-km-long fibre using 223 wavelength channels derived from a single microcomb ring resonator producing a stabilized dark-pulse Kerr frequency comb. We also present a theoretical analysis that indicates that a single, chip-scale light source should be able to support 100 Pbit s⁻¹ in massively parallel space-and-wavelength multiplexed data transmission systems. Our findings could mark a shift in the design of future communication systems, targeting device-efficient transmitters and receivers.

Frequency combs are a special type of light source, characterized by their spectral composition of equidistant frequency components resembling the teeth of a comb. As a source for lightwave transmission, these comb-like structures lend themselves well to wavelength division multiplexing (WDM), where data are modulated onto each comb line separately and transmitted simultaneously. A similar spectral structure can be created by combining an array of individual laser diodes, but this is more hardware intensive and thus less scalable for the growing needs of the internet. Individual lasers will also drift randomly in frequency, making the line spacing between any two lines fluctuate in time. To prevent cross-talk between data channels one therefore needs to account for buffer regions between laser lines where no data can be transmitted. By contrast, the frequency separation between comb lines will stay constant even if the whole comb drifts slightly. This allows for substantially smaller buffer regions, possibly eliminating them altogether. Not only does this allow better utilization of the spectral bandwidth, but a constant line spacing also allows for advanced signal processing. A second, but important property of frequency combs is that all comb lines are phase coherent, which enables joint digital signal processing among channels.

Frequency lines from a fibre-based supercontinuum source have proven useful to demonstrate record data rate transmission of 2.15 Pbit s⁻¹ (ref. 11) and 10.66 Pbit s⁻¹ (ref. 12). For practical applications, more compact solutions are desirable, and by leveraging photonic integration, chip-scale sources have recently been explored intently. These sources could enable mass production, offer small footprints, low cost, low driving power, and compatibility with other integrated components such as modulators and pump lasers. In an experiment specifically designed to investigate how much data a single source could carry, that is, where the light from the source is distributed evenly among all data channels simultaneously, a single nonlinear chip-based supercontinuum source was found to support 661 Tbit s⁻¹ (ref. 22). Among chip-scale designs, microcombs are attractively simple and...
only require a single continuous wave pump laser and an integrated microresonator to generate dissipative Kerr-cavity solitons. Two such rings were spectrally interleaved in ref. to achieve 50 Tbit s through a single-core fibre. Another class of microcomb sources producing dark-pulse Kerr (DPK) combs are gaining interest, as they yield an approximately tenfold higher pump-to-comb conversion efficiency than their bright soliton cousins, thus producing a higher optical signal-to-noise ratio (OSNR) and enabling higher modulation-order coherent communications. A third type of microcomb source that is gaining popularity is soliton crystals. They can potentially outshine DPK combs in conversion efficiency, but are limited to only covering the C-band, as shown in ref. , in which a soliton crystal was used to transmit 39.2 Tbit s through a single-core fibre in the C-band alone. A comparison of different dissipative Kerr-cavity soliton combs for transmission demonstrations is shown in Supplementary Note 1.

Here we report on a ring resonator designed to create a DPK comb covering the telecom C + L bands, and we experimentally investigate how much data this light can carry when transmitted through a 37-core single-mode fibre. We compare these results with a first-principles theoretical capacity model. Our results elucidate the potential of chip-scale comb sources to break through the petabit-per-second barrier when combined with advanced space-division multiplexing fibre technology.

**Results**

We begin by analysing the total capacity achievable using a frequency-comb source with a spectrum as the one seen in Fig. 1. Each comb line—with initial comb line power —corresponds to a spectral channel , which is power-divided into a number of spatial channels . We consider a model (see Fig. 1) similar to those in refs. , which track the noise generated throughout the system to arrive at a received signal-to-noise ratio (SNR) and ultimately set the limit on the achievable data capacity per channel through the Shannon–Hartley theorem. By assuming, for simplicity, no cross-talk between channels, and a flat spectrum, the total capacity is found by summing over all spectral and spatial channels:

\[ C_{\text{total}} = n_{\text{WDM}} m_{\text{SDM}} R_s \log_2 (1 + \text{SNR}) \]  

(1)

Where \( R_s \) is the symbol rate and the SNR is derived as:

\[ \text{SNR} = \frac{P_{\text{signal}}}{(N_{\text{Tx}} + K_{\text{link}}) N_{\text{link}}} \]  

(2)

Where \( P_{\text{signal}} \) is the signal power of a single channel \( (G_{\text{pre}} P_0) \), and \( N_{\text{Tx}} \) and \( N_{\text{link}} \) are the noise power spectral densities (PSDs) for the transmitter and link, respectively, with:

\[ N_{\text{Tx}} = (N_{\text{comb}} + N_{\text{pre}} + N_{\text{SDM}}) V + N_{\text{mod}} \]  

(3)

The transmitter contains a series of amplifiers \( (G_{\text{pre}}/\text{SDM}/\text{mod}/\text{link}) \) that counteract losses at each stage at the cost of additional noise. The factor \( V \) accounts for polarization filtering and modulator-induced spectral broadening. Further details and mathematical derivations are presented in the Methods.

Note that the SNR depends on the channel bandwidth (which is equal to \( R_s \)) and the number of SDM channels through the SDM noise term \( (N_{\text{comb}}) \) as the comb lines are power-divided into \( m_{\text{SDM}} \) channels and subsequently amplified, adding noise. The number of WDM channels is generally set by the bandwidth of the comb source and the equipment, whereas the number of possible SDM channels directly relates to how many times the power can be split and amplified before the OSNR is too low to allow data transmission. For telecommunication purposes, we will limit ourselves to a 10 THz bandwidth covering the C- and lower L-bands (1,530–1,610 nm), and compare comb sources of different initial values of \( P_0 \).

By contrast to ref. , we focus on calculating the total capacity as a function of the number of SDM channels for a variety of different sources. This is shown in Fig. 2, in which we used realistic parameters to calculate the SNR (see Methods). The frequency-comb sources are assumed to have full spectral efficiency whereas the multiple laser sources are modelled with an additional spectral guard band of 5 GHz between the lines to compensate for realistic laser frequency drifts. Although full spectral efficiency is difficult to achieve in practice due to non-idealities in the transmitter, the necessary guard band can be substantially reduced below 5 GHz.

The different comb sources have line powers varying from −30 dBm to −10 dBm, based on performances from various published...
to generate a DPK comb identical to the set-up in Fig. 2e. An illustration of the ring resonator and the simulated time-domain profile is shown in Fig. 3a.

As opposed to bright solitons, the DPK comb consists of a broad high intensity background with a periodic dip; the dip is caused by switching waves connecting two stable points in parameter space and allows for a generally higher output power (with a conversion efficiency of 13% in this experiment), quantified as the fraction of the pump (other than the pump line) converted into comb power. The chip’s output spectrum can be seen in Fig. 3b together with a numerical simulation. The power in the lowest line is −13 dBm, which is consistent with the parameters investigated in Fig. 2a and shows the possibility of using DPK combs to reach multi-petabit-per-second transmission rates.

The 105 GHz line spacing is too large for most widely accessible high intensity background. We therefore investigate the possibility of modulating the entire comb to generate additional frequency components and reduce the line spacing. This is done through an electro-optic Mach–Zehnder intensity modulator driven by a 35 GHz sine wave. Figure 3c shows the optical spectrum of the comb with and without modulation, revealing a tripling of the number of lines. The modulation introduces a loss of 10 dB due to modulation and insertion losses. As the average power per line scales with the number of lines, a larger ring with a 35 GHz line spacing would have very similar power per line at the expense of a more challenging fabrication process. In a set-up already employing $m_{\text{SDM}} \times n_{\text{WDM}}$ modulators, a single additional element brings about an insignificant increase in complexity. Furthermore, this can be offset and integrated in the near future with the rise of thin-film lithium-niobate-based modulators.

**Chip-scale comb performance of DPK**

To illustrate the potential of chip-scale DPK combs, we experimentally investigate a Si$_3$N$_4$-based microring resonator with a line spacing of 105 GHz (ref. 40). The chip is pumped by a continuous wave external-cavity laser with 28 dBm on-chip power at 1,562 nm, to transmit 1 Pbit s$^{-1}$, over 80 km using 32 Gbaud.

**Petabit-per-second transmission**

To investigate the scalability of a chip-scale comb source for data transmission, we performed a transmission system experiment using the 105 GHz (modulated to 35 GHz) DPK comb source described above. Through thermal feedback to on-chip micro-heaters, the DPK comb
is maintained in the same comb state for tens of hours at a time. In the experimental set-up, the DPK comb is amplified after modulation, after which each line is optically filtered out and data are modulated at 32 GBaud in two polarizations. This leaves a guard band of 3 GHz, which, although lower than the 5 GHz assumed for a full laser-array source, is much larger than what has been demonstrated for microcombs, where guard bands as low as 600 MHz have been displayed. We modulate 223 different comb lines with data \( n_{\text{WDM}} = 223 \), omitting the middle lines due to filtering away the pump, and the outer lines due to bandwidth limitations of our optical filters. This leads to a total transmitted bandwidth of 7.8 THz. After data modulation, all wavelength channels are combined in the same fibre and split 37 ways. The 37 paths are decorrelated and propagated in parallel through a 7.9-km-long 37 core fibre.

A switch and an optical passband filter selects one core and one comb line at a time. In this way, all 8,251 \( n_{\text{WDM}} \times n_{\text{DOM}} \) channels are individually detected, demodulated and processed to estimate the information transfer rate.

The data are processed offline and verified to have a bit error ratio of \(<10^{-5}\) after a low-density parity-check (LDPC) decoding, assuring error-free transmission after an additional outer forward error correction (FEC; see Methods for details). The achieved rate is plotted for each wavelength channel in Fig. 4 in terms of bit per symbol per core. The achieved rate varies across different wavelength channels. Each core has the same achieved rate by design. From the measured SNR we calculate the capacity limit from the Shannon–Hartley theorem. The calculated rate is plotted for each core (light blue diamonds) and averaged over all cores (dark blue circles).

In summary we have analysed the capacity of massively parallel space and wavelength division multiplexing systems driven by frequency combs. We demonstrate that chip-scale microcomb sources can break through the petabit-per-second frontier in spite of the frequency lines being two orders of magnitude lower in power than multi-laser sources, and only utilizing 91% of the channel bandwidth.

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References


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Methods

Capacity model

Our model is based on estimating the SNR of the transmission signal by starting with the initial comb source's noise PSD, $N_0$. This noise is then amplified by the preamplifier with gain $G_{\text{pre}}$, which amplifies the comb lines to the desired signal launch power:

$$N_{\text{comb}} = N_0 G_{\text{pre}}$$  (4)

The amplifiers not only amplify the existing noise, but also contribute with a spontaneous emission noise PSD defined as:

$$N_i = 2n_{\text{sp}}hv(G_i - 1)$$  (5)

where $h$ is Planck’s constant, $v$ is the optical frequency, $x$ represents the label on the optical amplifier ('pre', 'SDM', 'link' or 'mod'), $G_i$ is the gain factor and $n_{\text{sp}}$ corresponds to a noise figure of 4.5 dB.

The power is divided into $m_{\text{SDM}}$ channels, which reduces both the signal and the noise power. This is compensated for by the SDM-amplifier with the gain $G_{\text{SDM}}$ set equal to the power splitting loss $(1/m_{\text{SDM}})$; therefore, the only increased noise at this point is the spontaneous emission:

$$\frac{N_{\text{comb}} + N_{\text{pre}}}{m_{\text{SDM}}} + N_{\text{SDM}} = N_{\text{comb}} + N_{\text{pre}} + N_{\text{SDM}}$$  (6)

Each SDM channel is now split into $n_{\text{SDM}}$ channels, where the WDM splitter only filters out $\Delta v$ around each comb line. The data are then modulated onto the comb lines, which spectrally broadens the comb lines and the noise over the entire modulation (channel) bandwidth so that the noise is spread over $R$, $\Delta v$. Assuming that the modulated noise does not spread into neighbouring channels, that is, $\Delta f_{\text{ch}} > \Delta v$, $\Delta f_{\text{ch}}$ is the channel spacing, the remaining noise after the WDM filter and modulator is reduced by the factor $V = \frac{1}{2 R \Delta v}$, where the factor of one-half accounts for a polarization filter in front of the modulator. All losses in the modulation process ($\alpha_{\text{mod}}$) are compensated by an amplifier afterwards, providing the gain $G_{\text{mod}} = V^{1/\Delta v}$ and adding additional ASE noise given by $N_{\text{mod}}$ resulting in a noise PSD of the full transmitter, $N_{\text{tx}}$, of:

$$N_{\text{tx}} = \frac{V^{1/\Delta v}}{2 R \Delta v} (N_{\text{comb}} + N_{\text{pre}} + N_{\text{SDM}}) + \frac{1}{\Delta v} \frac{G_{\text{mod}}}{G_{\text{comb}}} + N_{\text{mod}}$$  (7)

where the factor of one-half accounts for a polarization filter.

The losses in the links are now compensated in a similar way by amplifying the existing noise ($N_{\text{tx}}$) and adding ASE in the form of $N_{\text{link}}$:

$$N_{\text{tx}} \times \frac{h G_{\text{link}}}{2} + N_{\text{link}}$$  (8)

For calculations we assume the sources cover 10 THz of spectral bandwidth. The frequency-comb sources assume a WDM channel spacing of 32 GHz and a modulation rate of 32 GHz leading to maximum spectral efficiency. The laser sources are modelled with a 37 GHz WDM channel spacing and a 32 GHz modulation rate. The 5 GHz excess spacing allows for frequency drift of the lasers and corresponds to the performance of state of the art commercial external-cavity lasers.

We assume a channel bandwidth filter of the same magnitude as the WDM channel spacing. As the derivation of $V$ above only holds for $\Delta \ll R_o$, our calculations use $V = \frac{1}{2}$ to represent the polarization filtering.

The OSNRs of the comb sources are calculated assuming a noise floor of –58 dBm, in line with the two polarization zero point energy limit in a 0.1 nm reference bandwidth ($\frac{1}{2} \times B_{\text{ref}} \times 2$), whereas the OSNRs of the laser arrays are assumed to be 60 dB as in ref. 34.

The laser sources assume a minimum line power of 15 dBm, which means the preamplifier and modulation amplifier are unnecessary and $G_{\text{pre}} = G_{\text{mod}} = 1$ (which leads to $N_{\text{pre}} = N_{\text{mod}} = 0$).

Furthermore, the one-laser-per-channel source also assumes $G_{\text{sdm}} = 1$, as each laser is not split by a power divider.

For all types of sources we assume a single link span of 80 km. Although it is not shown here, our model predicts the same as ref. 34 for longer spans, where the signal becomes dominated by the link noise. In this case the frequency-comb sources are still competitive due to their improved spectral efficiency.

Comb generation, operation and electro-optic modulation

The microring resonator is fabricated in Si$_3$N$_4$ with a SiO$_2$ cladding on silicon using a subtractive processing method with a width and a height of 1,850 nm and 600 nm, respectively. The device has a circular geometry with a radius of 227 μm. The device features a mean intrinsic Q-value of 10.9 × 10⁶ and a platinum micro-heater. We initialize the comb by thermally shifting the resonance towards the pump laser using the micro-heater. The initialization is assisted by an avoided mode crossing between transversal modes. Although the location of the modal crossing cannot be engineered with this geometry, recent advances in photonic molecules allow for generating DPK microcombs in a controllable and reproducible manner with a comparable bandwidth, line spacing stability and power per line to the microcomb in this experiment. During initialization and operation, the pump stays blue-detuned with respect to the resonance, enabling a passive thermal locking of the detuning, the comb state is actively stabilized by monitoring the comb power, filtering the pump from the output and feeding back to the micro-heater. The feedback system is a field-programmable gate array-based proportional-integral control loop that allows for advanced relocking patterns, enabling practical day-to-day operation of the comb. The open loop 3 dB feedback bandwidth of the micro-heater system is 10 kHz. When locking the comb state to a specific comb power level, a stable DPK comb state can be maintained over days (with a standard deviation of the peak amplitude fluctuations of 3.5%). The comb is pumped with a continuous wave external-cavity laser at 1,562 nm with a 10 kHz linewidth and an output power of 6 dBm. The pump is amplified by a high-power erbium-doped fibre amplifier, and coupled on and off the chip with lensed fibres with a coupling loss of 2 dB per facet. The on-chip power was estimated to 28 dBm by comparing detailed simulations with the output spectrum of the comb. The lensed fibres are mounted to piezo controlled stages, which continuously reoptimize the alignment using an external feedback loop. The spectrum of the comb right after the chip spans 90 nm, has 105 GHz line spacing and 13 dBm power in the lowest line. Amplification is done right after the chip by separating the comb into the C- and L-bands using WDM splitters, and amplifying each band individually. Each band is then electro-optically modulated at 35 GHz to reduce the line spacing, at the cost of 10 dB loss. The modulation is achieved using one Mach–Zehnder intensity modulator for the C- and L-bands, separately, each driven by a pure 35 GHz sinusoidal tone. The bias voltages of the modulators are adjusted to obtain a linear transfer function and thereby no discernable higher-order sidebands. After modulation the bands are amplified again. Due to bandwidth limitation in our C-band amplifiers the comb lines below 1,525 nm are lost. More information about the comb generation can be found in Supplementary Note 2.

System experimental scheme

The system-level experiment uses the generated comb specified above. For data modulation the wavelength channels are separated into odd and even channels, and data modulated with independent dummy data at a rate of 32 Gbaud. A single-wavelength channel is loaded with a third set of data and designated the channel-under-test (CUT). All of
the wavelength channels are successively designated as CUT to evaluate the comb performance in the entire bandwidth.

Data modulation is performed by single polarization I/Q modulators and an arbitrary waveform generator with a sampling rate of 64 GSa s$^{-1}$. Forward error correction is applied to the data using LDPC block codes with 33% overhead for the 64 QAM formats, and 50% for the 256 QAM formats. The modulation format is chosen depending on the SNR of each wavelength channel. This SNR is measured by sending a pilot transmission through the fibre core with the highest loss. We employ probabilistic shaping following a Maxwell–Boltzmann distribution and tailored to the SNR of each channel with the help of a distribution matcher$^{50,51}$. The modulation signal is pulse shaped by root-raised cosine filter with a roll-off factor of 0.01 and 401 taps. A polarization multiplexing emulator with a 1924 symbol delay between the two polarizations is used to decorrelate the data in each polarization. After data modulation all wavelength channels are combined in the same fibre and split 37 ways. An amplifier is used before the splitting to ensure a minimum of 0 dBm in each path. The 37 paths are decorrelated and propagated in parallel through a 7.9-km multicore fibre$^{34}$. The launch power into the fibre is 9 ± 1 dBm per core.

This set-up differs from the theoretical model in that we assume the spatial splitting happens before data modulation. This is done due to the limited number of available data modulators. In practice, this decreases the transmitted OSNR, as the noise from the amplifier used before the splitting is not filtered by the polarizer in the data modulator. We therefore have more noise in our experimental system than in the equivalent theoretical model, and our experiment therefore constitutes a worst case scenario.

A switch on the receiver side selects one core at a time, which is spectrally filtered to isolate the CUT before being detected in a standard dual-polarization coherent receiver. We observe a total average loss of 26 dB from input to the 1:37 splitter to the output of the receiver switch. This loss includes the power splitting, free space fan-in/out and fibre propagation losses. The average signal power into the receiver is −4 dBm, together with a 15 dBm local oscillator for offline digital signal processing. The transmission experiment was repeated for each wavelength channel through each of the 37 fibre cores.

The digital signal processing flow starts with low-pass filtering, resampling and synchronization. A T/22-spaced pilot-aided radius-directed adaptive equalization with 221 taps is used for polarization demultiplexing, chromatic dispersion compensation, and compensating the imperfect frequency response of the transmitter and receiver. The pilot overhead is 4%. A decision-directed phase-locked loop is then used for frequency offset correction and carrier phase recovery. The signal is LDPC decoded to evaluate performance. The bit error ratio is verified to be below 10$^{-9}$ as this well-known error floor caused by LDPC codes can be removed using an outer hard-decision forward error correction (HD-FEC) code with 1% overhead$^{12}$. Both the pilot overhead and the HD-FEC overhead are subtracted from the total capacity to arrive at 1.84 Pbit s$^{-1}$. A detailed description and illustration of the experimental set-up is available in Supplementary Note 3.

Data availability
The datasets and code for recreating the figures are available at ref. 53 as processed measurement results. The raw oscilloscope traces are available on reasonable request. Source Data are provided with this paper.

Code availability
The algorithms used for the digital signal processing at the transmitter and the coherent receiver are standard and are outlined in detail in the Methods. MATLAB scripts can be provided by the corresponding authors on reasonable request.

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Author contributions
A.A.J, M.R.H and Z.Y. developed the technique for generating and stabilizing the DKP comb source, and were supervised by M.G., J.W.T. and V.T.-C. D.K. designed the transmission experiment set-up, and H.H. and M.G. provided suggestions. A.A.J., D.K., M.R.H. and F.K. constructed the experimental set-up and performed the transmission experiment, and were supervised by H.H., M.G, J.W.T. and L.K.O. D.K. performed the data analysis of the transmission experiment data. L.K.O., D. K. and A.A.J. performed the theoretical modelling of transmission capacity. The overall concept was conceived by L.K.O., M.G., P.A., A.L., M.K., V.T.-C. and T.M. H.E.H., M.Y. and S.F. wrote and implemented the probalistic shaping technique. Z.Y. fabricated the microring resonator, and was supervised by V.T.-C. and P.A. O.B.H. aided in numerical simulations of DKP combs, and was supervised by V.T.-C., P.A. and J.S. Y.S. and K.A. designed and produced the multicore fibre. T.M. identified the fibre for the experiment. The manuscript was written by A.A.J, D.K., L.K.O and V.T.-C. All authors discussed the data.

Competing interests
V.T.-C and O.B.H. are co-founders of Iloomina, a start-up company that offers prototyping services for silicon nitride.
Additional information
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