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**Abstract:** Interleaving two soliton Kerr combs we generate 179 carriers for WDM transmission and demonstrate transmission of a data stream of 50 Tbit/s over 75 km. This is the highest data rate achieved with a chip-scale comb source.

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## 1. Introduction

Optical frequency combs can provide a multitude of optical carriers for massively parallel wavelength-division multiplexing (WDM) [1,2]. The fixed frequency grid minimises inter-channel guard bands, thereby increasing spectral efficiency (SE). In addition, comb lines do not exhibit stochastic frequency variations, which has been identified as the major obstacle for compensating nonlinear propagation impairments [3,4]. For highly integrated communication systems, chip-scale comb sources are of particular interest, among which Kerr comb generation in nonlinear microresonators [5] represents a particularly attractive option due to the large achievable bandwidth and the small optical linewidth of the individual carriers. Kerr combs are suited for coherent communications [6], and previous transmission experiments based on cavity solitons [7] have led to net data rates of 19.7 Tbit/s [8]. However, in these experiments, SE was limited to 2 bit/s/Hz due to the large ratio of free spectral range (FSR) and symbol rate.

In this work, we use interleaved Kerr frequency combs for massively parallel WDM transmission of 179 channels spanning the telecommunication C and L bands. The reduced line spacing and the increased symbol rate lead to a much improved SE of 5.2 bit/s/Hz. We demonstrate an aggregate net data rate of 50 Tbit/s, which is, to the best of our knowledge, the largest data rate achieved with a chip-scale comb source so far. We show that isolated comb lines do not show any penalty compared to a high-quality external cavity laser (ECL) source.

## 2. Full C- and L-band transmission experiment

The experimental setup is depicted in Fig. 1(a). Two frequency combs with an FSR of 95.8 GHz each are independently generated, frequency tuned, and interleaved. For emulating WDM transmission, we modulate even and odd comb lines independently, transmit the data stream over 75 km, and measure the bit error ratio (BER) for each channel. The combs are generated by parametric frequency conversion in Kerr-nonlinear silicon-nitride ($Si_3N_4$) microresonators (Fig. 1(b), $Q \approx 7\times10^5$), which are pumped [7] by a continuous wave (cw) ECL. Polarisation controllers (PC) and erbium-doped fibre amplifiers (EDFA) are used to adjust polarisation and pump power. The on-chip pump power is about 2 W. Band-pass filters (BPF) suppress amplified spontaneous emission (ASE) noise from the pump EDFA. Lensed fibres (LF, coupling loss 1.5 dB) couple light to and from the SiN microresonator chips. Fibre Bragg gratings (FBG) are used to suppress residual pump light. For proper interleaving we thermally tune the centre frequency of the combs, leaving the FSR unchanged, and we match their optical power with a variable optical attenuator (VOA). The combined combs are amplified by a C+L-band EDFA before the line powers are equalized and dis-interleaved into even and odd carriers with two programmable filters (Finisar WaveShaper, WS), followed by four saturated EDFA. The odd (even) carriers of the C and L-band are combined using multiplexers (C/L MUX). The IQ modulators IQ1 and IQ2 are driven with pseudo-random bit sequence (PRBS) of length $2^{11}-1$ at 40 GBd
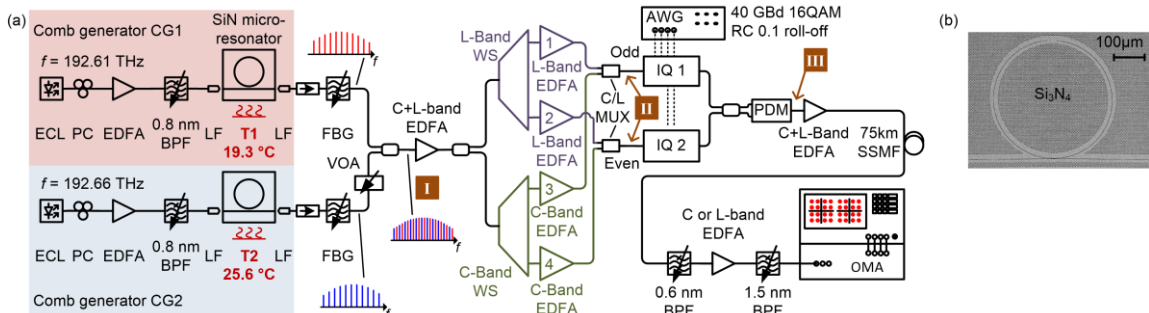


Fig. 1: (a) Soliton-comb generation in two SiN microresonators and data transmission setup. WDM is emulated by independently modulating even and odd carriers at 40 GBd with 16QAM and raised-cosine pulse shaping. After transmission over 75 km, BER in each channel is measured using an optical modulation analyser (OMA). The spectra at positions I, II and III are shown in Fig. 2. (b) SEM of the SiN microresonator.
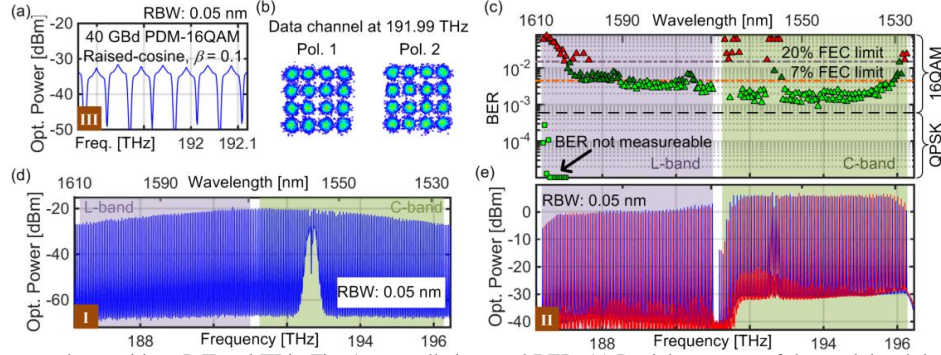
**Fig. 2:** Spectra measured at positions I, II and III in Fig. 1, constellations and BER. (a) Partial spectrum of the modulated data stream. (b) Constellations for the data channel at 191.99 THz. (c) Measured BER for each of the data channels. Light (dark) green triangles mark a BER below the 7% (20%) FEC threshold $4.5\times10^{-3}$ ($1.5\times10^{-2}$); red triangles indicate a larger BER; green squares mark 14 channels at the L-band edge which are operated with QPSK. (d) Spectrum of combined combs (e) Overlaid spectra of dis-interleaved and equalized lines.

using 16QAM and raised-cosine (RC) pulse shaping, roll-off factor $\beta = 0.1$. Polarisation-division multiplexing (PDM) is emulated by a split-and-combine method. Fig. 2(a) shows the spectrum for seven data channels. The data stream is amplified and transmitted over 75 km of standard single-mode fibre (SSMF). At the receiver we select each channel individually by a 0.6 nm BPF, followed by an EDFA and a 1.5 nm BPF. The signal is received with an optical modulation analyser (OMA, Keysight N4391A) which performs digital post processing. Exemplarily, the constellation diagrams for the data channel centred at 191.99 THz are depicted in Fig. 2(b). The measured BER ($10^6$ bits compared) for all channels is given in Fig. 2(c). A total of 126 channels (light green triangles) perform better than the BER threshold ($4.5\times10^{-3}$) for forward-error correction (FEC) with 7% overhead (OH), and 39 channels (dark green triangles) are better than $1.5\times10^{-2}$ and require an FEC with 20% OH. The red triangles indicate BER values beyond these FEC limits, caused by strong ASE noise of the pump EDFA near 192.61 THz and 192.66 THz, by a power drop of the carriers at the outer edges of L and C band, or by a mismatch between the C/L MUX and the C-band WS passbands, which affects the lines at the low-frequency edge of the C band. The outer 14 channels at the low-frequency edge of the L band cannot be used with a 16QAM modulation format, and we transmit a 40 GBd PDM-QPSK signal (green squares) instead. In total, a net aggregate data rate of 50.1 Tbit/s is obtained.

## 3. Comb lines vs. ECL: A comparison

In a second set of experiments we compare the performance of a single comb line for transmitting 16QAM data with that of a high-quality ECL as a reference. Both sources are operated at the same optical signal-to-noise power ratio (OSNR). It turns out that in our setup the comb line does not exhibit any penalty with respect to the ECL. For this comparison we use comb generator CG2 in Fig. 1 without VOA and 3 dB couplers. After C+L-band amplification, the C-band WS selects a single line (0 dBm at $\lambda_2 = 1550$ nm). Alternatively, a line power of 16 dBm is supplied by the ECL at equal wavelength. After EDFA 3, line power is adjusted to 24 dBm for both cases. After modulating with PDM-16QAM at 40 GBd, we substitute the C+L-band ED-FA and SSMF with a setup for noise loading and OSNR measurement. Fig. 3(a) shows the spectra for comb line and ECL. The spectral shoulders are due to amplifier noise, see Fig. 3(a), and limit the maximum OSNR for the comb line to 42 dB. For three comb lines and for the corresponding ECL carriers, Fig. 3(b) displays the BER as a function of OSNR$_{ref}$ (reference bandwidth 0.1 nm). The curves are indistinguishable for such wavelengths. The error floor stems from transmitter nonlinearities and from receiver noise. The black line indicates the theoretical BER.
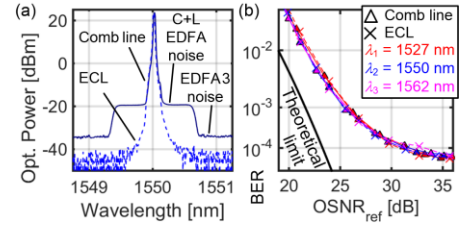


Fig. 3: Comparison of isolated comb line with ECL. (a) Spectra before modulation. (b) Measured BER vs. OSNR$_{ref}$, using PDM-16QAM at 40 GBd.

## 4. Summary

We demonstrate WDM data transmission at 50 Tbit/s using carriers from two interleaved microresonator-generated Kerr combs. In our setup, isolated comb lines do not show any OSNR penalty compared to a high-quality ECL.

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