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Abstract: Dark-pulse microresonator combs exhibit efficient pump-to-comb power conversion. Using on-chip pump powers of 21 dBm, we show 20-channel PM-64QAM-based data transmission. These results represent the highest-order modulation format encoded onto any integrated comb.
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1. Introduction

Microresonator frequency combs are generated by utilizing the Kerr effect in a nonlinear optical cavity [1]. The resonator can be designed so the spacing between the equidistant lines is on the order of tens of GHz, making it suitable for optical communications [2]. Recent experiments with silicon nitride-based combs have shown that they can operate in several multi-wavelength scenarios [3–6]. These devices could enable future chip-scale transceivers by allowing co-integration of the comb source with modulators and other components on a single chip [7].

Recently, a new class of mode-locked microresonator combs, consisting of circulating dark pulses has been demonstrated [8]. These comb states display high pump-to-comb power conversion efficiencies [9]. This is of significant interest in the context of optical communications as it can allow for chip-scale comb sources requiring only moderate pump powers. Here we present the first dark-pulse comb transmission experiment. The high conversion efficiency allowed us to reach the highest-order modulation format used with any integrated comb source to date. We performed 80 km transmission with 20 parallel data channels using 20 GBd PM-64QAM. The on-chip pump power was about 21 dBm, a level compatible with state-of-the-art chip-scale laser sources [10]. This shows the potential for dark-pulse combs as light sources in fully integrated multi-wavelength transceivers.

2. Comb generation

The optical frequency comb shown in Fig. 1(a) was generated by pumping a high-Q (>1 million) silicon nitride microresonator [11] with a sub-10 kHz linewidth continuous-wave pump laser amplified to 25.6 dBm. We estimated the coupling losses to be 5 dB per facet, yielding an on-chip pump-to-comb conversion efficiency above 20% (as defined in [5]). To initialize the comb state, the pump laser was tuned from the lower wavelength side into a cavity resonance located at 1540 nm. Stable operation of the comb state over the measurement time was ensured by monitoring the power in the comb line at 1536 nm. That power was then used as feedback for adjusting the pump laser wavelength [12]. The resulting 230 GHz comb line spacing was set by the 100 µm ring radius. To verify the dark-pulse comb state, the time-domain waveform was measured at the resonator's drop port using a 500 GHz optical oscilloscope. The result is shown in Fig. 1(b). As the system's drop port was only weakly coupled to the ring, the through port was used instead for the data transmission experiment.
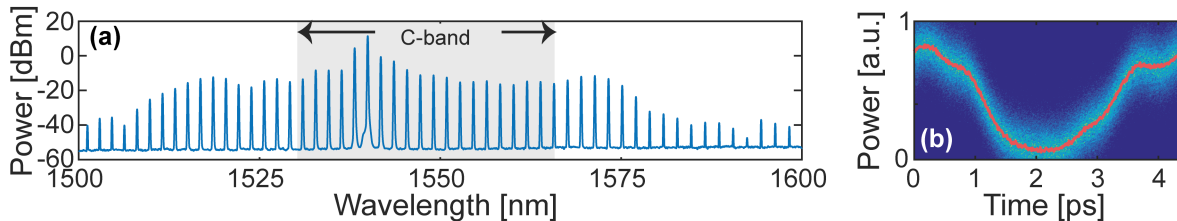

Fig. 1. (a) Optical spectrum (0.1 nm RBW) of the dark-pulse frequency comb used for the data transmission as seen at the output of the chip's through port. (b) The power of the intracavity waveform measured at the device's drop port.

3. Data transmission

The high power-per-line in the comb enables the usage of high-order coherent modulation formats. To demonstrate this in a system experiment, we modulated data onto 20 comb lines within the C-band (between 1531 nm and

1566 nm). The setup is shown in Fig. 2(a). Splitting the comb lines into two arms before modulation allowed sending independent data on neighboring channels and minimizing the number of carriers that were fed to a single modulator. The two random 20 GBd 64QAM data streams were generated using an arbitrary waveform generator (AWG) with a sequence length of 2^{16} symbols. To emulate a dual-polarized transmitter, a polarization-multiplexing stage with a 1 m (about 100 symbols) long decorrelation arm was included. The modulated carriers were then transmitted through an 80 km fiber link with all channels having above 33 dB OSNR (at 0.1 nm bandwidth).

A dual-polarized coherent receiver was used to receive each data channel individually. We used a tunable external-cavity laser (with <100 kHz linewidth) as local oscillator. The waveforms were recorded using a 23 GHz bandwidth real-time oscilloscope operated at 50 GS/s. The transmitted data symbols were then recovered offline using standard digital signal processing algorithms compensating for receiver, link and transmitter impairments. More than 9 million bits were decoded in each dual-polarized channel to calculate the received bit error ratio (BER). The results are shown in Fig. 2(b) with example received constellations displayed for both polarizations for the channel located at 1531 nm in Fig. 2(c). All channels had received BERs below $7 \cdot 10^{-3}$ allowing for the usage of hard-decision forward error correcting codes with 9.1% overhead [13]. The final aggregate data rate was 4.4 Tb/s.
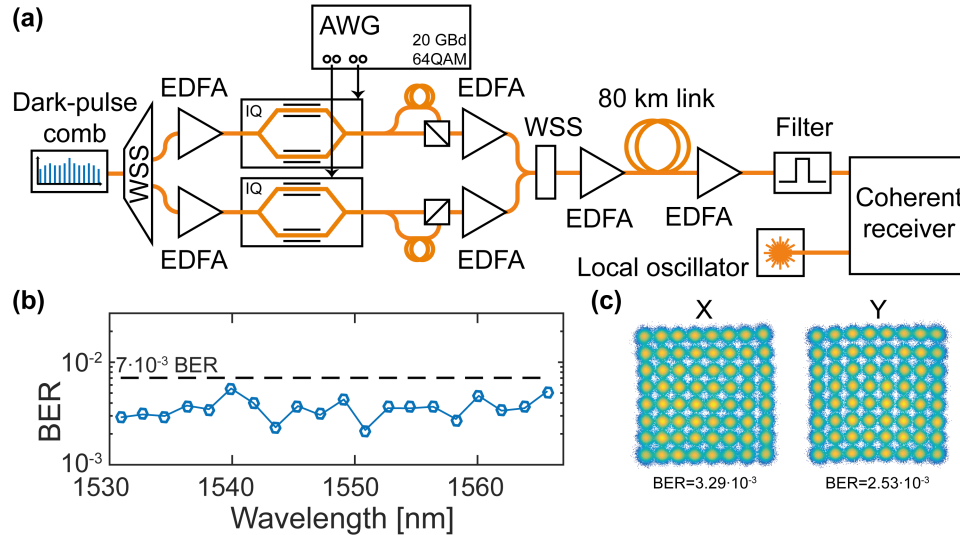

Fig. 2. (a) Schematic of the system setup. Two wavelength-selective switches (WSSs) were used to spectrally flatten the comb and compensate for the gain spectrum of the erbium-doped fiber amplifiers (EDFAs). The 20 GBd 64QAM data signal was generated using an arbitrary waveform generator (AWG). (b) Resulting bit-error ratios (BERs) for all 20 data channels allowing for error-free transmission using a hard-decision FEC [13]. (c) Received constellation diagrams and BERs for both polarizations for the channel at 1531 nm.

4. Conclusions

We have shown the first coherent data transmission experiment performed with a dark-pulse microresonator comb source as well as the highest-order data modulation encoded onto any integrated comb source. The off-chip pump power was kept below 26 dBm with an estimated on-chip pump level of 21 dBm. We have shown that dark-pulse combs are simultaneously compatible with high-order modulation formats and pump powers within reach of chip-scale lasers. This makes them an attractive light source for future chip-scale multi-wavelength transceivers.

5. References

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