IMDD Data Transmission with Microresonator Soliton Crystals

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Abstract: Intensity modulated direct detection data transmission using microresonator multi-soliton and 2-soliton crystal states are demonstrated. We achieve error free transmission of 10Gb/s NRZ data and BERs in the region of 10^{-4} with 28.05GBd/s PAM4 data. © 2024 The Author(s)

1. Introduction

Since their initial demonstration in 2014 [1], microresonator soliton frequency combs have rapidly gained popularity in many different domains. Most recently, their potential as optical sources for data communications have been extensively investigated, due to their small footprint, broadband spectral characteristics, and ease of generating multiple wavelengths of light with a single laser. This has made them well suited as a solution to the exponential increase data transmission and cost efficiency demands in high-speed data movement systems.

To date, most demonstrations of soliton frequency comb sources have been employed in coherent detection schemes [2, 3], which tend to incur higher overhead costs despite their high transmission capacity. In contrast, the transmission of demultiplexed wavelength comb line sources modulated with intensity modulated direct detection (IMDD) comes with significantly lower cost and complexity [4]. In this work, we explore the potential of broadband bright-soliton frequency combs as optical sources for IMDD systems, demonstrating up to 28.05 GBd/s PAM4 data transmission using a multi-soliton state, and error-free transmission of NRZ data at 10 Gb/s with the 2-soliton crystal (2-SC) state. This work represents the first demonstration of IMDD data transmission using the soliton crystal state generated in a SiN microresonator.

2. Soliton generation

The soliton frequency combs are generated in a silicon nitride (Si_3N_4) micro-ring resonator (MRR) with an intrinsic quality factor (Q_i) of 3.2 million in the auxiliary-assisted configuration [5], allowing for stable and repeatable generation of soliton states. In this configuration, the auxiliary laser is employed to maintain thermal stability of the resonance while the pump laser is electrically swept through, avoiding the chaotic modulational instability state that tends to accompany the all-optical single-pump soliton combs in the sub-THz free spectral range (FSR) regimes [6].

Figure 1 shows the setup used for frequency comb generation. The pump laser is swept through the resonance, with the characteristic soliton steps in the comb power trace observed using the oscilloscope (Fig. 2c) The multi-soliton state in this work corresponds to the step with the highest comb power and is initiated with the pump and auxiliary lasers located at 1565.38 nm and 1554.32 nm respectively. The soliton state can further be manipulated through the number of FSRs between the pump and auxiliary resonances [7], resulting in soliton crystal states that present with much higher comb powers compared to the single-soliton state.

The comb output from the MRR is then passed through a 90:10 splitter, where power from the 10% arm is used for continuous monitoring of the comb state during the experiment while the 90% arm is connected to the downstream high speed measurement setup. The individual comb lines are filtered into their closest International Telecommunications Union (ITU) bands using a dense wavelength division multiplexer (DWDM) and amplified using a pre-amplifier erbium-doped fiber amplifier (EDFA) before modulation and transmission. A band pass filter is used to reduce the SNR after amplification and is then modulated with a Mach-Zehnder modulator. A back-to-back configuration was used for the high-speed measurements.

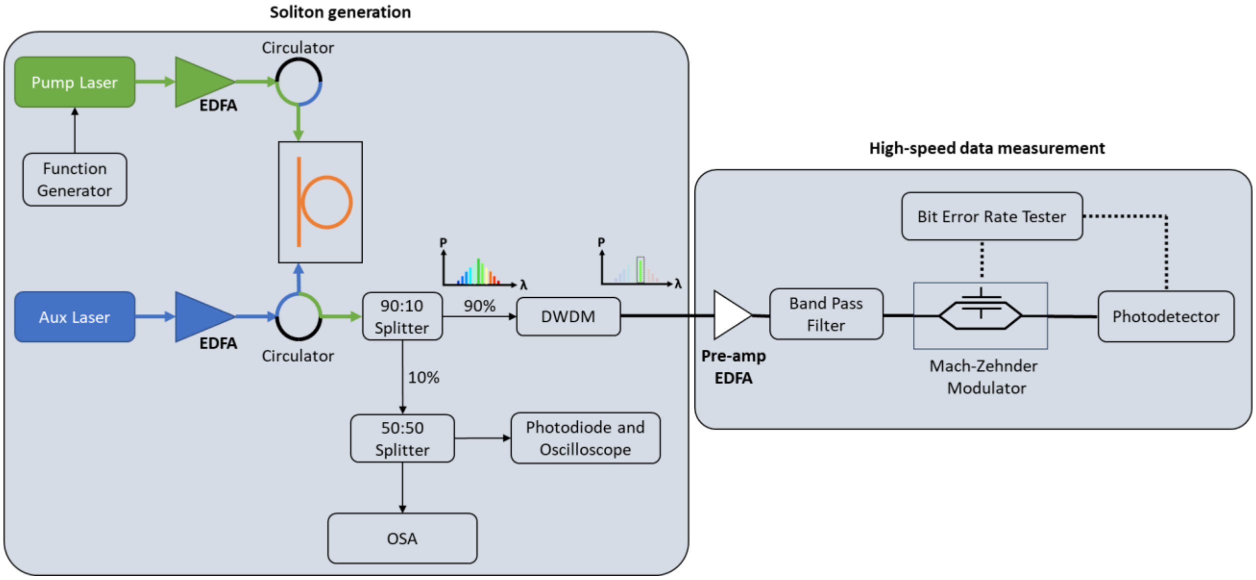

Fig. 1. Schematic of the experimental setup used in this work. EDFA: Erbium-Doped Fiber Amplifier, DWDM: Dense-Wavelength Division Multiplexer.

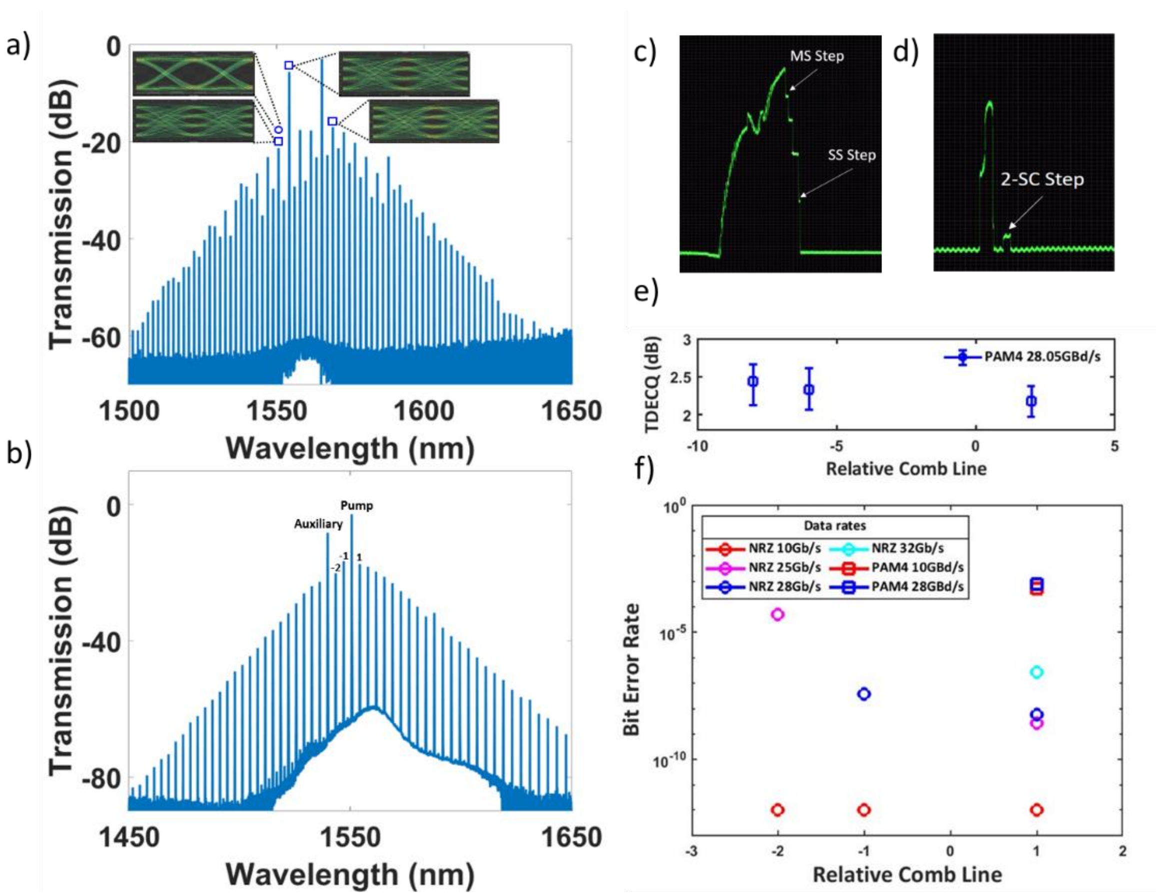

Fig. 2. Spectra of the microresonator-based generation of a) multi-soliton (MS) state b) 2-soliton crystal (SC) state. The inset shows the measured eye diagrams corresponding to data modulated on the labelled frequency comb lines.

Measured temporal output of the microresonator showing the soliton step for the c) MS and single-soliton state and d) 2-SC state. e) TDECQ measured for the respective comb lines for the MS state. f) Measured bit error rate for the respective comb lines with various data rates.

3. High-speed measurements

High-speed measurements were performed with IMDD transmission of several DWDM channels in the MS and 2-SC states. Figures 2 a and b show the spectra and the filtered comb lines for the MS and 2-SC states respectively while Figs 2c and d show their locations on the respective comb traces. The eye diagrams observed in the inset of Fig. 2a show an eye opening with the transmission of 28.05Gb/s NRZ and 28.05GBd/s PAM4 data, indicating undistorted transmission with the comb lines.

The transmitter dispersion eye closure quaternary (TDECQ) compares the optical power penalty to an ideal transmitter for PAM4 modulation with a minimum value of 1dB. The measured TDECQ values for the comb lines relative to the pump in the MS state are shown in Fig. 2e. The TDECQ values fall within 2 – 2.7dB, indicating high SNR in parallel to the open eye diagrams observed in the inset of Fig. 2a. Lastly, the measured bit error rates (BER) for the comb lines relative to the pump for the 2-SC state are shown in Fig. 2f at various data rates. The comb line on the right of the pump is modulated with 10 – 32Gb/s NRZ and 10 – 28GBd/s PAM4 data. At higher data rates of 25 – 32Gb/s, the BERs range between 10^{-6} – 10^{-8}. An error-free transmission of the data modulated on the comb lines is achieved with 10Gb/s NRZ data, as shown with BER of 10^{-12}.

With PAM4 data modulated on the frequency comb lines, the BERs fall in the region of 10^{-4}, showing a reasonably low BER considering PAM4 has a ~9dB reduction in the SNR as compared to NRZ modulation. The comb lines of the 2-SC state have comparably higher optical power compared to a single-soliton state, due to the spread of the optical power with greater FSR. Also, the comb line intensities of the MS state commensurate with the 2-SC state. Thus, we expect a lower optical power penalty for the MS and 2-SC state to achieve the same BER relative to a single-soliton state. Phase and intensity noise sensitivity with solitons are current limiting factors to achieve error-free IMDD transmission at high data rates and higher BERs are exacerbated by the ASE noise from amplification. Hence, obtaining higher comb power without requiring external gain that circumvents the modulator loss would be beneficial to IMDD data transmission.

4. Conclusion

We have demonstrated IMDD transmission with microresonator multi-soliton and 2-soliton crystal frequency comb states in an integrated silicon nitride microresonator, achieving error free transmission of 10Gb/s NRZ data and BERs in the region of 10^{-4} with 28.05GBd/s PAM4 data. The low BERs and open eye diagrams achieved are facilitated by the coherent nature of the multi-soliton and soliton crystal states generated in this work. This demonstration illustrates the potential for microresonator frequency combs to provide viable, more efficient and cost-effective light sources for transceiver systems adopting IMDD modulation formats.

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5. References

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