1.5 Terabit/s IM/DD Transmission with Kerr Soliton Frequency Comb for DCI Application

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Abstract: We experimentally demonstrate 1.575 Terabit/s aggregated transmission rate with 75 Gb/s on-off keying signal employing a dissipative Kerr soliton optical frequency comb. The system is scalable to provide multi-Terabit/s optical interconnects.

1. Introduction

The continuous increase in the use of artificial intelligence and machine learning necessitates significant changes to the subsystem design of next-generation optical interconnects for data centres (DC) and high-performance computing (HPC). Increasing the modulation order and signalling at higher symbol rates for transmission, along with utilizing parallel channels, can effectively meet the growing demands in DCI and HPC beyond 1 TbE [1]. There are different approaches for implementing parallel optical channels, such as using independent lasers or employing comb sources [2, 3]. However, using multiple tunable lasers will likely raise the system's cost and power requirements for the optical interconnects [4] and may require frequency locking, especially when operated at higher symbol rates.

Recent advancements in integrated photonic subsystems, including optical frequency combs, as well as innovative photonic integrated circuit architectures and components, have enabled the use of dense wavelength division multiplexed (DWDM) systems to meet specific requirements [5]. Integrated Kerr frequency combs present an appealing solution for high-density intensity-modulated direct-detection (IM/DD) DWDM systems [6]. Kerr combs provide an extensive bandwidth of over 5 THz with a line spacing of over 100 GHz, typical for DWDM spacing, and can be seamlessly integrated with other photonic devices [7]. In [8], authors have demonstrated using the Kerr comb with 25 GBd NRZ and PAM4 signals on four comb lines for optical switching in data centres. In [9], authors have demonstrated 20 Gb/s NRZ per channel (up to 640 Gb/s) transmission with Kerr comb-driven silicon photonic transmitter. The symbol rate was limited in all the previous demonstrations employing the Kerr comb for IM/DD systems.

This paper presents the experimental demonstration of a 1.575 Terabit/s OOK transmission with a signal operated at 75 GBd in each channel. Here, we use a dissipative Kerr soliton (DKS) optical frequency comb and demonstrate its potential as a simple and suitable candidate for a single-chip multi-wavelength optical source for the DCI system. At a pre-FEC BER of 1×10^{-2}, we achieve the receiver sensitivity of -13 dBm across 21 channels over 1 km fibre transmission. To the best of our knowledge, we present the first demonstration of the highest symbol rate OOK transmission with the Kerr comb for IM/DD application.

2. Experimental Setup and Device Characterisation

Figure 1 depicts the experimental setup for generating the DKS frequency comb, characterising it, and transmitting the 1.575 Terabit/s OOK signal using the selected comb lines. The generation of the DKS optical frequency comb employs a high-quality Si_3N_4 microresonator [7]. The table-top frequency comb source comprises a continuous-wave laser (CW pump), a high-quality microresonator, and electronics. Light coupled into the ring cavity builds in intensity with each roundtrip pass until the circulating optical power exceeds the material's nonlinear threshold to generate a wide range of frequencies, i.e., a frequency comb. The comb lines' free spectral range (FSR) is 100.13 GHz, primarily dictated by the physical dimensions of the microresonator. We measured a total optical power of 4 dBm for the entire comb. Figure 2 (a) shows the generated frequency comb having a 3-dB bandwidth of about 5.9 THz featuring a smooth spectral envelope with carriers spanning beyond the C and L bands. We also observe that the residual pump has a power of 10.5 dB larger than the generated comb lines, with an average comb line power of around -20 dBm.

First, we characterise the comb lines to measure the relative intensity noise (RIN). The comb was processed using a programmable optical filter (optical processor, waveshaper 1000s) to reduce the residual pump power and filter out the 21 DWDM lines of interest (1548 nm to 1567 nm). We measured an output power of -6 dBm for the filtered and gain flattened lines, and these lines were further attenuated by 6 dB before it was amplified to

20 dBm using a low-noise EDFA (LN-EDFA, LNA-220C-35-SM). Figure 2 (a) shows the filtered and amplified lines in the blue colour trace. The amplified output power was controlled before it was used for transmission or characterisation.

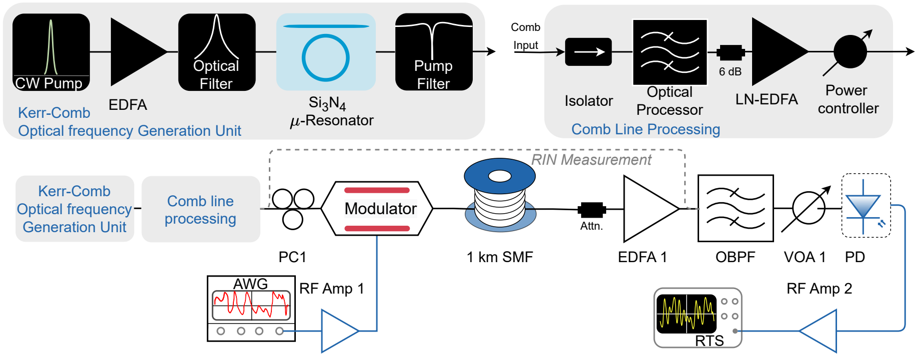
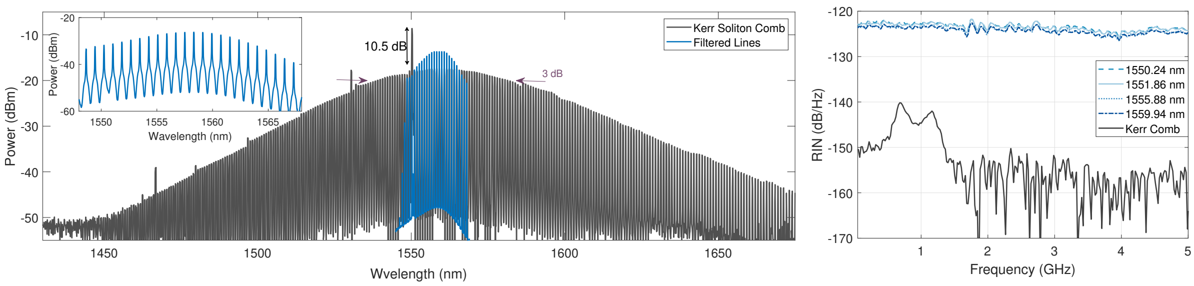


Fig. 1: Schematic of the experimental setup for generating the DKS optical frequency comb, characterising the comb lines, and transmitting 1.575 Tertabit/s data over single mode fibre.

We filter out each line using a wavelength tunable optical band pass filter (Alnair BVF-200, OBPF), fix the optical power using a variable optical attenuator (VOA 1) and detect it using a 30 GHz bandwidth photodetector (PD). The detected signal is then amplified using a 50 GHz RF amplifier and is fed to the electrical spectrum analyser (ESA). The electrical spectrum is then used to compute the RIN presented in Figure 2 (b) for the selected four comb lines across the spectrum. The optical signal-to-noise ratio (OSNR) of the unamplified comb lines of 32 dB implies a RIN of -147 dBc/Hz. After amplifying the comb to the required power, the RIN of the filtered comb lines, including the pump at 1550.24 nm, was increased to -124 dBc/Hz. The standard shot noise limit corresponding to the measurement power of -4.5 dBm is -151.4 dBc/Hz. The average RIN for the entire comb from the comb generator presents a level below -150 dBc/Hz. The RIN of all the filtered lines is degraded due to increased amplified spontaneous noise (ASE) from the amplification. The value of the RIN indicates that these lines can be efficiently used to transmit OOK signals.



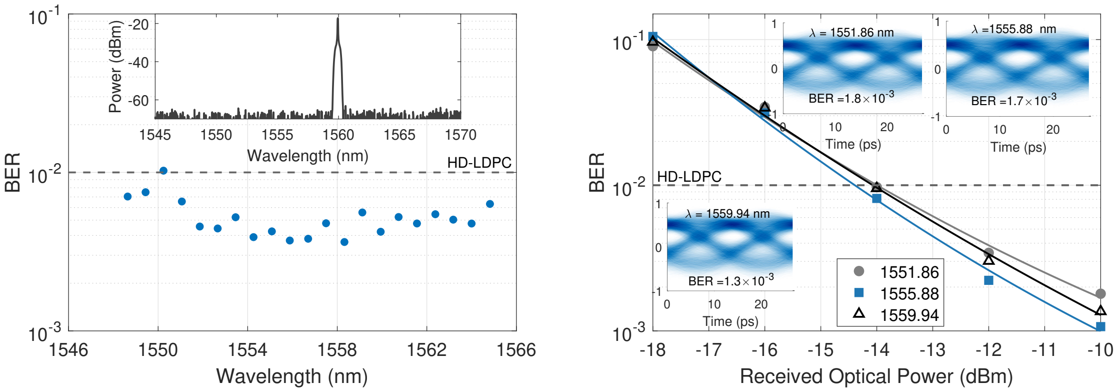
(a) (b)

Fig. 2: (a) Spectrum of the generated entire Kerr comb and the filtered and amplified portion for transmission (in blue colour). (Inset) Spectrum of the 1.575 Terabit/s modulated data. (b) Measured RIN of the filtered comb lines and of the entire comb.

3. Data Transmission: Results and Discussion

We then demonstrate a system-level intra-data centre interconnect distance transmission with a 75 GBd OOK signal over 1 km SMF. We generate the 75 GBd OOK signal offline as a part of transmitter-side digital signal processing (DSP). We apply root-raised cosine (RRC) pulse shaping with a 0.1 roll-off factor to reduce the electrical bandwidth to less than 42 GHz and load it in the arbitrary waveform generator (AWG), operating at 225 GSa/s sampling rate. A 30 GHz external modulator modulates the light source to the output of the comb line processing unit, driven with the amplified (using RF Amp 1) 75 GBd OOK electrical signal. The spectrum of the modulated comb is shown as an inset in Fig. 2. The modulated 75 Gb/s/λ signal over 21 DWDM lines from the comb is transmitted 1 km standard SMF with a launch power of 4.5 dBm. The transmitted signal is amplified using an EDFA (EDFA 1, Optilab) with high saturation output power. We filter out each amplified line using a wavelength-tunable optical bandpass filter (Alnair BVF-300, OBPF). The filter bandwidth and channel spacing are sufficient, so the cross-channel interference is negligible. To estimate the receiver sensitivity, we vary the signal power at the receiver (received optical power, ROP) using VOA 1. The attenuated signal is then detected using a 70 GHz photodetector, amplified using a 16 dB gain RF amplifier and digitized using a 70 GHz bandwidth real-time scope (RTS, 256 GSa/s). The system operates within an overall bandwidth of 30 GHz, determined primarily by the limited bandwidth of the optical modulator.

In the receiver-side offline DSP, we first resample the signal from 256 Gs/s to the symbol rate and perform matched filtering with the RRC prototype filter. We use a linear transversal feed-forward equaliser (FFE) with 21 T-spaced taps. We use a slightly increased tap size to reduce the effect of component-induced ISI due to their non-flat response in the desired bandwidth. Figure 3(a) shows the BER performance of the 1 km transmitted 1.575 Terabit/s OOK signals as a function of the channel wavelength at a fixed ROP of -13 dBm. The BER performance of all the 21 lines, constituting a total data rate of 1.575 Terabit/s, attains a BER below the standard hard decision low-density parity check code (HD-LDPC) limit of 1×10^{-2}. The spectrum of the filtered channel at 1559.94 (line 15) is shown as an inset in Fig. 3(a). The slight variation in the performances is attributed to the variation in ASE noise from the amplifiers in these channels. We then perform the ROP variation of three selected lines to identify the receiver sensitivity. Figure 3(b) shows the BER performance as a function of ROP for selected lines, and the performance falls within the HD-LDPC limit for ROP >-14 dBm and within the HD-FEC limit (BER = 3.8×10^{-3}) for ROP >-12 dBm. The inset of Fig. 3(b) shows the eye diagram of the signal of the three lines at an ROP of -10 dBm. The opening of the eye diagrams in all the cases is a visual measure of the performance, indicating an arbitrarily low error on FEC encoding. Even with bandwidth limitations in the outlined system



(a) (b)

Fig. 3: BER performance of 75 GBd OOK signals after 1 km SMF as a function of (a) wavelength index at -13 dBm ROP and (b) received optical power for selected lines, and (inset) eye diagram of the three signals at -10 dBm ROP.

and relatively larger RIN (mainly from the EDFAs used), the performance of broadband DKS frequency comb is within the FEC limits. Through the improved design of the Si_3N_4 resonator and integration technologies, it will be feasible to enhance the efficiency of the comb generation and the power per line in the comb, thus improving RIN and potentially enabling PAM4 transmission.

4. Conclusion

This work achieved an OOK transmission speed of 1.575 Terabits per second using 21 lines for a broadband DKS frequency comb and a 30 GHz MZM in the C-band for short-reach systems. Our results show the highest IM/DD symbol rate transmission per line with the DKS comb and demonstrate performance within an HD-LDPC FEC limit. This architecture is scalable and has the potential to support high-capacity links using hundreds of wavelength channels, allowing for multi-Terabit/s photonic interconnects.

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