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I-CReST 2025:163-119 – Analysis of Soliton Microcomb Dynamics for Energy-Efficient WDM Data Centre Interconnects

Ikhwan Naim Md Nawi[1]*, Ahmad Fakhrurrazi Ahmad Noorden[2], Nurkhaizan Zulkepli[1], Ahmad Farid Abidin[3], Abdel-Baset M. A. Ibrahim[4]

[1]*Centre of Foundation Studies, Universiti Teknologi MARA, Cawangan Selangor, Kampus Dengkil, 43800 Dengkil, Selangor, Malaysia.*
[2]*Centre for Advanced Optoelectronics Research, Department of Physics, Kulliyyah of Science, International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia.*
[3]*Faculty of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.*
[4]*Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.*

*E-mail: ikhwannaim@uitm.edu.my

ABSTRACT

Conventional wavelength-division multiplexing (WDM) links in data centres rely on multiple discrete lasers, which are power-hungry and scale poorly in energy efficiency. Optical frequency combs produced in integrated microresonators, known as soliton microcombs offer a compelling alternative by providing many wavelength channels from a single laser pump, drastically reducing the energy per bit for WDM transmission. In this work, we present an analysis of soliton microcomb dynamics tailored for energy-efficient WDM data centre interconnects. We model the generation of dissipative Kerr solitons under realistic low-power conditions and evaluate key metrics such as pump power, conversion efficiency and per-line power. Our results show that a microcomb source can produce a broad set of WDM carriers with high spectral purity while operating at a fraction of the power consumption of multi-laser arrays. With pump powers on the order of tens of milliwatts, conversion efficiencies of about 50% to 70% can be achieved, yielding per-channel optical power on the order of 1 mW. This is significantly lower than per-channel outputs of individual lasers. We further demonstrate that the microcomb-based WDM transmitter can improve the energy-per-bit by an order of magnitude compared to legacy architectures. This analysis underscores that soliton microcombs enable energy-efficient scaling of data centre interconnect bandwidth. By consolidating multiple channels into one miniature comb source, overall transmitter power is minimised, paving the way for high-capacity and low-energy optical links in future green data centres.

Keywords: Soliton microcomb; Lugiato-Lefever equation; wavelength-division multiplexing; data centre interconnects; Kerr frequency comb

1. INTRODUCTION

Conventional short-reach wavelength-division multiplexing (WDM) links in data centres are reliant on multiple discrete lasers, such as arrays of external cavity diode, distributed Bragg reflector (DBR) or distributed feedback (DFB) lasers, which are power-hungry and scale inadequately in energy efficiency [1], [2]. Each wavelength channel typically requires its own laser source, leading to high aggregate power consumption and complex packaging for N-channel transmitters. Additionally, the management of numerous free-running lasers including wavelength stabilisation and thermal adjustment result in additional overhead. As data-centre traffic grows, these inefficiencies exacerbate operational costs and energy usage. Optical frequency comb sources have recently emerged as a compelling alternative to discrete laser arrays [3]. A single frequency comb can produce a multitude of phase-locked wavelength channels from a single pump laser, drastically reducing the per-channel power overhead and simplifying the transmitter design. Soliton microcombs, which are frequency combs produced in chip-scale Kerr microresonators, provide an appealing pathway to energy-efficient WDM links by consolidating numerous optical carriers into a single miniature device.

Soliton microcombs are made possible by dissipative Kerr solitons (DKS) in nonlinear resonators, first demonstrated around 2013-2014 [4]. In a seminal experiment, Herr et al. generated stable femtosecond soliton pulses in a high-Q silicon nitride microring resonator, corresponding to a low-noise comb of evenly spaced lines in the frequency domain [4]. This breakthrough provided a means to harness microcombs as coherent multi-wavelength sources. Soon after, researchers exploited microcombs for telecom applications. Marin-Palomo et al. demonstrated that a singular microcomb source, powered by a continuous-wave pump laser, could substitute around 180 individual lasers in a WDM communication experiment, attaining nearly 50 Tb/s of data across 179 channels throughout the C and L bands [5]. Such demonstrations underline the potential of microcombs to replace large banks of lasers with one chip-scale source, drastically improving energy-per-bit. Similarly, in recent years, ultra-high-capacity connections have been reported, such as the transmission of 44.2 Tb/s over 75 km of fibre in the C-band using a soliton crystal microcomb [2].

Building on this progress, we propose an analysis of soliton microcomb dynamics for energy-efficient WDM data centre interconnects. We study dissipative Kerr solitons in realistic low-power situations such pump outputs of tens of milliwatts. We then evaluate data centre transmitter performance parameters such energy-per-bit for comb-based WDM links, per-line output power, and pump-to-comb conversion efficiency. We then estimate power reductions by comparing these parameters to traditional multi-laser WDM devices.

2. METHODOLOGY

To analyse soliton microcomb dynamics, we employ the Lugiato-Lefever Equation (LLE) as a mean-field model for the nonlinear cavity field. The LLE is a proven framework for Kerr microresonator combs [6], capturing the balance of dispersion, nonlinearity, cavity loss, and driving that leads to dissipative soliton formation. In its temporal form, the LLE can be written as a damped and driven nonlinear Schrödinger equation, given by:

$$\tau_R \frac{\partial E(\phi,t)}{\partial t} = \left[-\frac{\kappa}{2} - i\Delta_0 + i\frac{\beta_2 L}{2}\frac{\partial^2}{\partial \phi^2} + i\gamma L|E|^2\right]E + \sqrt{\kappa_{\text{ext}}}E_{\text{in}}. \quad (1)$$

Here, $E(\phi,t)$ is the intra-cavity field envelope as a function of fast time, t and angular coordinate, ϕ along the ring, τ_R is the round-trip time, $\kappa = \kappa_0 + \kappa_{\text{ext}}$ is the total cavity loss rate consisting of intrinsic loss and coupling loss, Δ_0 is the laser-cavity detuning, β_2 is the group velocity dispersion, γ is the Kerr nonlinearity coefficient, L is the cavity length and E_{in} is the pump field amplitude. This mean-field equation originally formulated by Lugiato and Lefever in 1987 [6] describes the evolution of the intracavity field over many round trips.

We solve the LLE numerically using a split-step Fourier method (SSFM) implemented in MATLAB. The SSFM integrates the cavity field equation by alternating between nonlinear Kerr steps and linear dispersion with loss steps in small time increments, effectively simulating the buildup of comb dynamics over time. This approach is standard and has been shown to accurately reproduce experimental microcomb behaviour [7]. We assume parameters corresponding to an ultra-low-loss Si_3N_4 microring resonator [8], [9]. In our simulations, the resonator free spectral range (FSR) is on the order of 100 GHz and the intrinsic Q-factor is between 10^6 and 10^7, such that parametric oscillation occurs at pump powers of only a few tens of milliwatts. We initiate the SSFM with a noise seed and slowly sweep the pump laser into resonance [10] until a stable single-soliton state is obtained.

We evaluate two key metrics from the simulation output namely the conversion efficiency and per-line power. The pump-to-comb conversion efficiency, η is defined as the fraction of input pump power converted into the comb, as given by:

$$\eta = \frac{P_{\text{comb}}}{P_{\text{pump}}} \quad (2)$$

where P_{comb} is the total power in the generated comb lines that shows the integrated power in all sideband frequencies and P_{pump} is the input pump power. This metric indicates how efficiently the microresonator translates pump energy into useful comb output. In practice, achieving high η is challenging for single-soliton states because a significant fraction of the pump often remains unconverted and it sits under the soliton spectrum. However, recent advances have pushed efficiencies above 50% in microcombs [11].

The per-line power is simply the comb power divided by the number of comb lines within the useful bandwidth. For an approximately flat-top comb spectrum, one can estimate the per-line power based on the equation:

$$P_{\text{line}} \approx \eta \frac{P_{\text{pump}}}{N_{\text{lines}}} = \frac{P_{\text{comb}}}{P_{\text{pump}}} \cdot \frac{P_{\text{pump}}}{N_{\text{lines}}} = \frac{P_{\text{comb}}}{N_{\text{lines}}} . \quad (3)$$

High per-line power is desirable to directly drive modulators without extra amplification but there is a trade-off where generating more comb lines or broader spectrum tends to spread power more thinly, reducing power per line [12]. Our analysis focuses on operating points that maximize efficiency and yield sufficient power per channel for data centre link budgets.

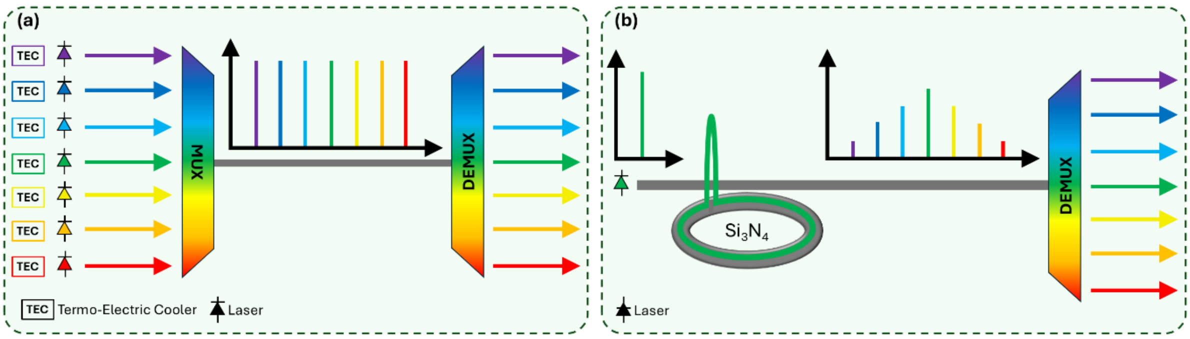

Fig. 1. Architecture of **(a)** a conventional WDM transmitter, and **(b)** microcomb-based WDM transmitter, for data centre interconnects.

Fig. 1(a). illustrates the mechanism of wavelength division multiplexing (MUX) and demultiplexing (DEMUX) in a conventional WDM transmitter used in data centre interconnects. Thermal-electric coolers (TECs) are employed to regulate the temperature of each laser, and numerous lasers are employed to produce a variety of wavelengths. An illustration of soliton microcomb generation in a high-Q Si_3N_4 microring resonator is depicted in Fig. 1(b). A comb of evenly spaced lines is produced because of the pump laser being calibrated into resonance and forming a circulating soliton pulse in the cavity. Modern microcombs can achieve high conversion efficiency and closely uniform per-line power, rendering them a viable alternative to multiple lasers in WDM systems.

In our methodology, we combine theoretical modelling using the LLE to capture soliton comb physics with numerical simulation (SSFM) to obtain realistic microcomb performance metrics. We simulate under low-power conditions of about tens of mW pump, consistent with chip-integrated lasers [13] and extract the comb characteristics relevant to WDM interconnects. These are then compared to equivalent legacy WDM transmitter parameters using multi-lasers to quantify potential energy savings. All simulations assume a single-soliton Kerr comb in the anomalous dispersion regime, unless otherwise noted.

3. RESULTS AND DISCUSSION

Using a pump laser power of approximately 20 mW, our simulations reach a stable single-soliton state in a Si_3N_4 microring of FSR ≈ 100 GHz. Fig. 2(a). shows the power spectral density of the comb repetition rate, confirming the stable single-soliton state. The sharp single peak confirms stable single-soliton operation. Fig 2(b). illustrates comb spectrum in the frequency domain. The comb spectrum shows multiple evenly spaced carriers. The generated comb spans about 20-30 nm in the C-band, roughly $N \approx 16$ lines of usable channels spaced by 100 GHz. We find the pump-to-comb conversion efficiency, η to be in the range of 50-70%, depending on detuning. In other words, more than half of the pump power is converted into the comb lines, with the remainder exiting as residual carrier. This high efficiency is consistent with recent experimental reports of soliton microcombs achieving 50% or greater conversion by optimizing cavity coupling or using photonic molecule resonators [14].

Notably, researchers have demonstrated $> 50\%$ efficiency by tailoring the pump mode via an auxiliary coupled cavity and have also achieved 30-50% efficiency using mode-locked dark pulses in normal dispersion microresonators [11]. Our simulated efficiency of 0.5-0.7 approaches these state-of-the-art values, indicating that efficient comb operation is attainable at milliwatt-level pump powers. It also significantly surpasses the typical few-percent efficiency of traditional multi-wavelength lasers, which is at best in the 10-20% range [15].

Crucially, this high η translates into low required power per channel. In our simulation, a 20 mW pump with $\eta \approx 0.6$ yields a total comb output of 12 mW spread across 16 lines, averaging about 0.75 mW or −1.25 dBm per line. The strongest comb lines carry on the order of 1 mW or 0 dBm of optical power, while the weaker lines at the edges of the spectrum carry a few tenths of a milliwatt. These per-line power levels are remarkably low compared to the outputs of individual typical DFB lasers, where it might emit 5-10 mW or 7-10 dBm of optical power in datacom [15].

Our findings suggest that a microcomb-based transmitter can operate with per-channel powers of 0 dBm or lower while still maintaining high signal quality. In a recent experiment by Geng et al. (2022), an integrated soliton microcomb laser produced 7 WDM lines with powers ranging from +1.5 dBm down to –10 dBm [12]. All those lines were used to transmit data without any optical pre-amplifier at the transmitter. This highlights a significant advantage of comb sources, as each channel is derived from the same laser, they all exhibit the same narrow linewidth and phase noise characteristics. In our simulation, the pump laser is assumed to be self-injection-locked to the microresonator, which yields comb lines with excellent coherence and low phase noise. Thus, the spectral purity of microcomb lines is high, despite the reduced absolute power per line, which is significantly higher than that of a noisy DFB laser array [10].

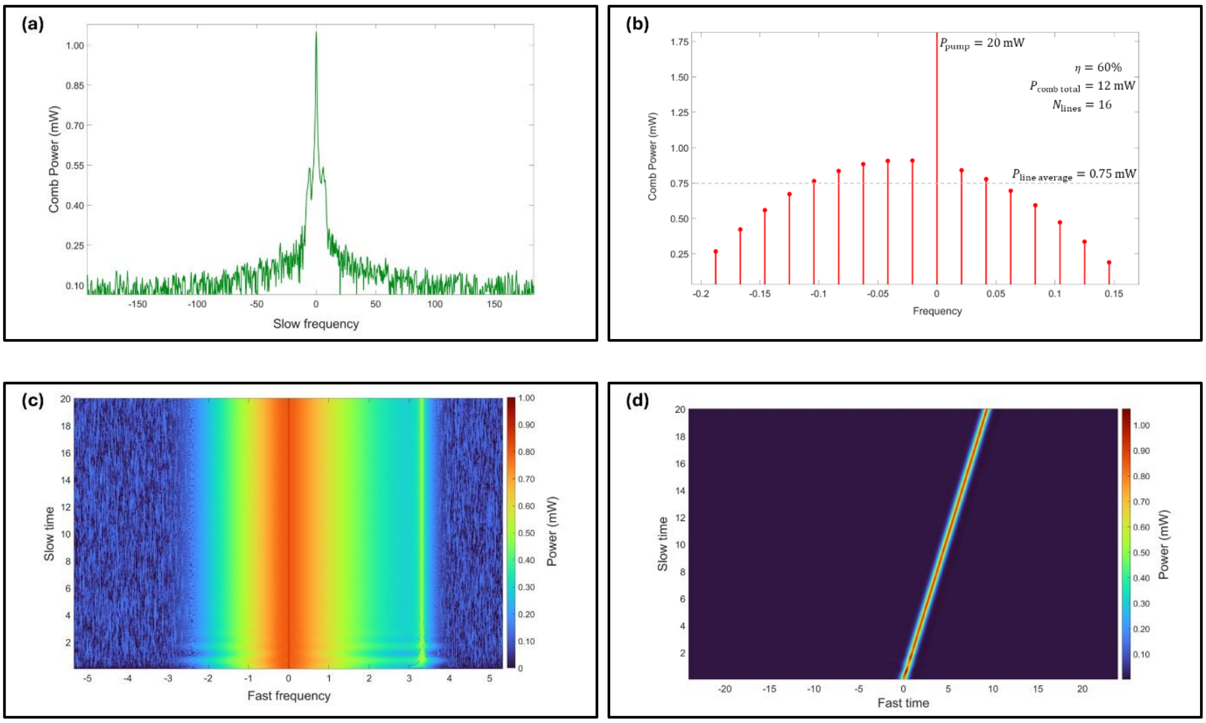

Fig. 2. Simulation illustrations of soliton microcomb. **(a)** Power-spectral density for the repetition rate of the comb beatnote. **(b)** Comb power with frequency domain, showing the analysed pump power, conversion efficiency, total comb power, number of comb lines and average power line. **(c)** Slow time vs. fast frequency, showing the evolution of the microcomb profile. **(d)** Slow vs. fast time, showing the soliton starting its existence and drifting towards the right.

The ultimate metric for data centre interconnects is energy consumption per transmitted bit. Our analysis suggests that soliton microcombs can bring a dramatic reduction in this metric at the transmitter side. In a conventional 16-channel WDM module, if each laser consumes 100 mW of electrical power to deliver 10 mW optical power, the total source power might be on the order of 1.6 W for the lasers alone. In a microcomb transmitter, one pump laser such as an external cavity diode, DBR or DFB laser at 100 mW could replace all 16 lasers. Even including the microresonator's dissipation, the optical power needed is only 20 mW for the pump. This translates to a drastically lower laser electrical power budget. A quantitative study by London et al. (2019) indeed found that a comb-based silicon photonic link had the lowest power per channel when compared to various laser-array architectures and could achieve 0.3-0.4 pJ/bit optical energy efficiency under optimized settings. This is an order-of-magnitude improvement over typical non-comb links, which often run in the tens of pJ/bit range for short reach [1].

Our simulated comb of 0.75 mW per channel at 25 Gb/s corresponds to about 0.03 pJ/bit in optical power. If we assume higher-order modulation or multiplexing to reach 50-100 Gb/s per channel, the optical energy per bit drops below 10 fJ. The most significant point is that the comb source itself contributes minimal overhead where it operates at a modest bias and employs a single laser instead of multiple ones. The microcomb offers a wide range of carriers with a high mutual coherence from a spectral perspective.

The slow time versus fast frequency map in Fig. 2(c). shows the buildup of the microcomb profile or the comb formation process, with power concentrated around the central frequencies and extending outward. Initially, we inject noise into the system. As the pump laser is tuned into resonance, modulation instability sets in, generating sidebands. Over time, these evolve into a stable soliton spectrum. Fig. 2(d). depicts the soliton drift in time, indicating the stable propagation of the soliton pulse within the cavity. The soliton locks to the cavity round-trip time and propagates stably. This temporal stability is essential and without it, the comb would fluctuate, degrading signal quality in WDM channels. These results validate that our simulations capture both the spectral and temporal dynamics of soliton microcombs. Critically, our simulation reproduces experimental observations of the transition from chaotic states to a stable single soliton. This confirms the validity of our model and gives confidence in applying it to data-centre-scale systems.

A comparison between a conventional 16-laser WDM transmitter and an equivalent soliton microcomb source is presented in Table 1. Even without any system optimizations, the microcomb uses only one pump laser with the power of 20 mW to generate 16 carriers, whereas the laser-based transmitter would require 16 lasers with the power of 10 mW for each laser for a total output of 160 mW. The comb approach still provides significant savings in optical power per bit, even though not all the laser power is utilised in modulation, as some is lost due to coupling and filtering.

Table 1. Comparison of a conventional multi-laser WDM transmitter versus a soliton microcomb source for 16 channels. These numbers are based on representative values from experiments [1], [12], [15] and our simulations.

WDM Transmitter Source	16 Discrete Lasers	Soliton Microcomb
Number of lasers	16 (one per channel)	1 (shared by all 16 channels)
Total optical output required	160 mW	12 mW (20 mW pump with 60% converted)
Per-channel output power	10 mW (10 dBm) each	0.75 mW (−1.25 dBm) each
Energy per bit (at 25 Gb/s)	0.4 pJ/bit	0.03 pJ/bit
Footprint and integration	Discrete laser array such as external cavity diode, distributed Bragg reflector (DBR) and distributed feedback (DFB) lasers	Monolithic microcomb source

In our results, the 20 nm comb bandwidth could be expanded by using dispersion engineering or higher power. The number of usable channels from a comb is ultimately limited by the link's wavelength routing such as AWG or filter bank bandwidth and the desired data rate per channel. For data centres, typically 4-8 Tb/s per fibre is a target where it consists of 32 wavelengths at 100 Gb/s each. A single soliton microcomb can easily supply 32 low-noise lines spaced at 100 GHz or 200 GHz. In fact, Pirmoradi et al. (2025) recently demonstrated an integrated 32-channel source that achieved 53% conversion efficiency and only 2.5 fJ/bit demux energy at 1 Tb/s aggregate rate. This was achieved by utilising a 200 GHz-FSR soliton comb and a monolithic demultiplexer [8]. These results align well with our analysis.

4. CONCLUSION

This analysis demonstrates that soliton microcombs enable a profoundly energy-efficient scaling of data centre interconnect bandwidth. By replacing many discrete lasers with one miniature comb source, the overall transmitter power can be minimized while still providing a wide array of wavelength channels. Our modeling of microcomb dynamics under realistic low-power operation of 10-20 mW showed high conversion efficiencies of 50-70% and per-line powers about 1 mW, sufficient for direct modulation in short-reach links. These attributes result in a substantial reduction in energy per transmitted bit, estimated to be 0.03 pJ/bit or less at the optical source. This is a significant improvement over legacy WDM transmitters. Equally important, the comb produces carriers that are mutually coherent and stable, simplifying WDM system design and improving performance. The high spectral purity and phase stability of soliton microcombs have already enabled multi-Terabit demonstrations with advanced modulation formats, confirming their viability for real data-centre environments. In future green data centres, transmitter modules can be imagined in which a single integrated laser-microcomb device supplies multiple modulators to drive dozens of wavelengths, resulting in a significant reduction in the laser count, power consumption, and cost per Gb/s. Recent prototypes of comb-driven transceivers have shown promising results in this direction. Challenges remain, such as further improving comb initiation and integrating the pump laser on the same die.

In conclusion, soliton microcomb technology offers a clear path to energy-efficient, high-density optical interconnects. By leveraging the physics of dissipative Kerr solitons in high-Q microresonators, we obtain a multi-wavelength light source that inherently scales in channel count without a proportional increase in power. This is a fundamental shift from the traditional one-laser-per-channel paradigm. The work presented here quantified the improvements in efficiency and outlined the favourable dynamics of high conversion efficiency and low noise per line that make it possible. As integration techniques continue to develop, we anticipate that comb-based WDM links will become a fundamental component of next-generation data centres. This will allow for continued bandwidth expansion with significantly reduced power consumption per bit. The soliton microcomb thus stands out as a key enabler for future optical networks that are both high-capacity and energy-efficient.

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