COMPUTING WITH FIBER-OPTICS SOLITONS

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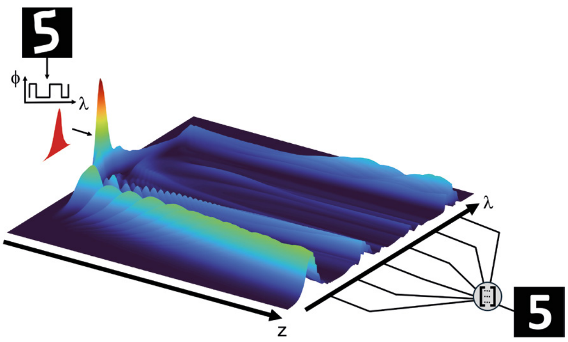

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Optical solitons, discovered in optical fibers fifty years ago, have long been celebrated as robust manifestations of nonlinear wave physics. Initially conceived as candidates for long-haul communications, their role has since evolved toward a broader landscape of nonlinear dynamics and ultrafast photonics. In one of their most recent applications, they have emerged as computational blocks for optical machine learning. Nonlinear fiber dynamics naturally generate high-dimensional feature spaces, robust nonlinear transformations, and femtosecond-scale processing speeds, properties that electronics cannot match.

In this perspective, we focus on soliton-inspired optical computing, with particular emphasis on fiber-based extreme learning machines (ELMs). We highlight recent experimental demonstrations and numerical modeling that establish soliton propagation as a potential powerful computational substrate. We also discuss opportunities and challenges for taking advantage of nonlinear fiber dynamics in machine learning, from multimode soliton processors to hybrid integrated systems, and argue that solitons may enable the next generation of ultrafast, energy-efficient, and noise-resilient computing.

The discovery of optical solitons in fiber optics in the early 1970s marked a milestone in nonlinear science [1]. Solitons, formed from the balance of Kerr nonlinearity and chromatic dispersion, represent self-organized states of light propagating without distortion over long distances. Fiber solitons were first extensively studied in the context of high-capacity telecommunications systems, driving many advances in the design of modern optical systems. More recently, they have had major impact in the development of broadband supercontinuum light sources, where soliton dynamics play a central role in driving the spectral broadening. Beyond these applications, solitons have influenced diverse areas of physics and served as a versatile testbed for nonlinear wave theory. Today, solitons are again finding a new application, this time as computational primitives for optical computing. As electronics approach fundamental speed and energy limits, nonlinear photonics provides an attractive route to achieve ultrafast, energy-efficient information processing. Solitons, with their robustness, dynamics, and compatibility with ultrafast lasers, provide a natural basis for optical machine learning hardware.

FIBER-OPTICS SOLITONS AS COMPUTATIONAL PLATFORM

The benefit of optical computing lies in harnessing the intrinsic properties of light: massive parallelism, ultrahigh bandwidth, and the ability to harness its nonlinear response. Within the different photonic computing approaches, extreme ●●●

learning machines (ELMs) have emerged as particularly well suited to implementation in optical systems due to their simplicity. In contrast to deep neural networks, ELMs avoid iterative training of hidden layers: the input weights are fixed by the physics of the medium, while only the output weights are optimized in a linear step. This approach maps naturally onto nonlinear fiber propagation, where data encoded on ultrashort pulses evolves under the nonlinear Schrödinger equation, producing a complex and high-dimensional representation of the input in a single pass. Essentially, the fiber acts as a physical "kernel generator," projecting input data into a rich feature space that can then be linearly processed for learning or classification tasks.

Soliton dynamics provide particularly powerful routes for this kind of dimensionality expansion. Indeed, processes such as soliton fission, dispersive wave generation, and Raman-induced frequency shifts diversify the temporal and spectral content of the light field in a highly nonlinear yet deterministic manner. These mechanisms effectively create a broad set of nonlinear kernels, where the resulting spectral (and temporal) patterns are both high dimensional and sensitive to the encoded input. Such features directly correspond with the requirements of machine learning, providing natural bases for classification, regression, and other data-driven tasks. In this way, soliton-induced dynamics transform optical fibers into functional learning machines, bridging nonlinear wave physics with modern computational standards.

IMPLEMENTATION

Recent advances by several groups have provided both experimental and numerical evidence that soliton dynamics can serve as the basis for optical machine learning. In our own recent experimental study [2], highly nonlinear fibers were used to implement an extreme learning machine, where input data encoded onto the spectral phase of femtosecond pulses was transformed through nonlinear propagation (see Figure 1 for a concept illustration). Task-independent analysis based on principal component analysis (PCA) showed that the effective computational dimensionality depends strongly on fiber length, dispersion regime, and input power, with up to 100 independent components generated under optimal conditions. These intrinsic metrics highlight how nonlinear propagation enriches the feature space, even though maximal spectral broadening does not necessarily correspond to maximal dimensionality. Task-dependent evaluation, using the MNIST digit recognition benchmark, confirmed that performance is optimum at intermediate power levels where dimensionality expansion is balanced by output consistency. The MNIST database is a widely used machine learning dataset consisting of 70,000 images of handwritten digits 0–9. Using this task, the system achieved a classification accuracy of 88% exceeding the linear baseline 82% when encoding 40 PCA and demonstrating that reliable computational features emerge before the onset of nonlinear instabilities.

Complementary numerical simulations [3], based on the generalized nonlinear Schrödinger equation, provided further insight. A realistic numerical model of a fiber-ELM reproduced classification accuracies exceeding 90% and showed how parameters such as dispersion profile, encoding strategy, and readout bandwidth shape performance. The simulations also studied the role of intrinsic noise, with anomalous-dispersion soliton fission suffering more from noise penalties, while normal-dispersion operation proved more robust.

Similar conclusions were reached in other recent demonstrations of neuromorphic computing based on soliton dynamics [4] where the coherent cascade of nonlinear dynamics enabled digital operations such as XOR, efficient classification of benchmark datasets, and even real-world tasks such as COVID-19 diagnosis in a compact fiber platform. More broadly, supercontinuum generation has been benchmarked as an analog computing element [5] with detailed parameter scans showing that the rich spectral diversity of the continuum acts as a universal function approximator and improves neural tasks such as autoencoding. The concept of nonlinear inference capacity was also recently introduced in fiber-optical extreme learning machines [6], showing that increasing optical nonlinearity can scale the computational depth to a level that can compete with deep neural networks.

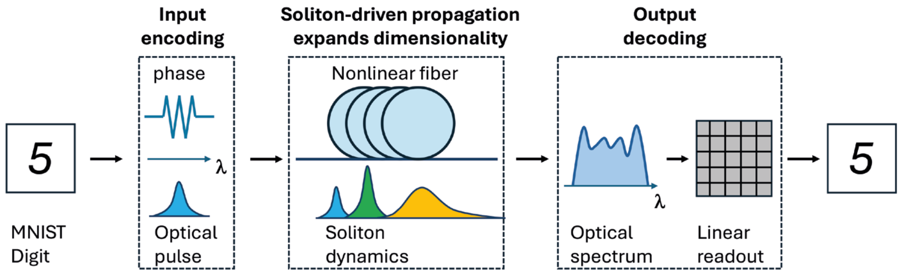

Figure 1. Concept of soliton-based optical computing. Input data encoded onto ultrashort pulses propagates through a nonlinear fiber where soliton dynamics expand the dimensionality of the signal. The resulting high-dimensional spectral features are processed by a linear readout enabling machine learning tasks such as digit classification.

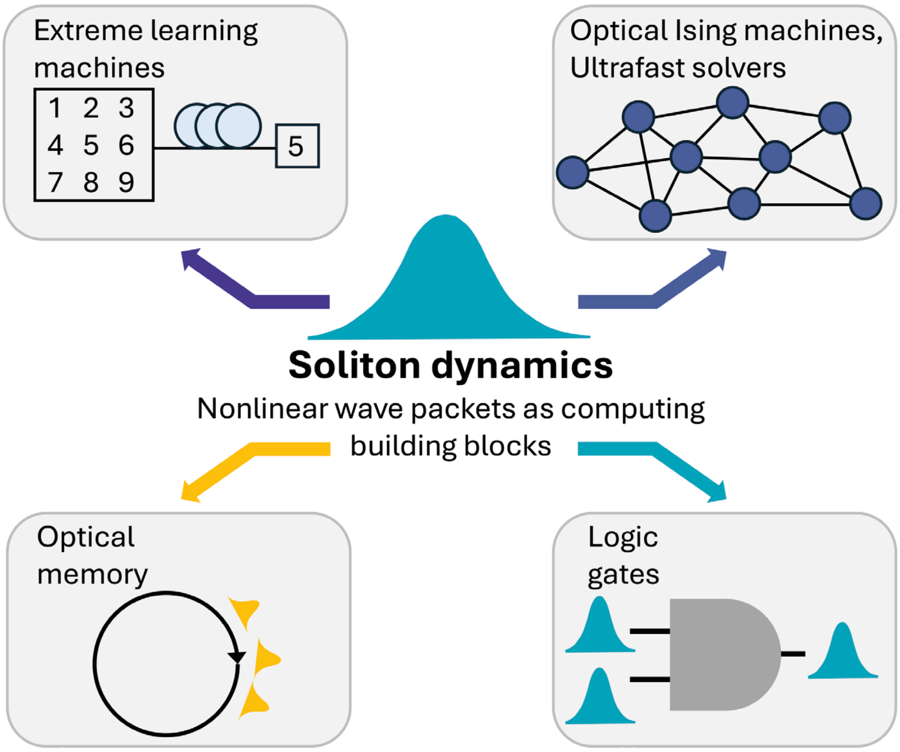

Figure 2. Applications of solitons as computational building blocks. Soliton dynamics provide a versatile platform for optical computing. Their robustness and nonlinear interactions enable a range of applications, including extreme learning machines for data classification, optical Ising machines and ultrafast solvers for optimization, optical memory based on circulating solitons, and logic gates constructed from soliton collisions and interactions.

Together, these results highlight a key distinction from electronic machine learning hardware. In electronics, nonlinear mappings are explicitly programmed into layered architectures, and dimensionality is expanded through iterative matrix operations. In contrast, soliton-driven fiber propagation physically generates a high-dimensional feature space in a single ultrafast pass, with dynamics governed by well-understood nonlinear physics rather than algorithmic construction. This makes the fiber itself a tunable kernel generator, inherently parallel, ultrafast, and energy efficient. In this sense, soliton dynamics provide not just an optical analog of electronic accelerators, but a new computational substrate well suited for machine learning.

FUTURE DIRECTIONS

Looking ahead, soliton-based computing opens several promising directions. Using multimode fibers would allow spatiotemporal solitons, orbital angular momentum states, and intermodal interactions to provide additional computational degrees of freedom, effectively expanding the dimensionality. Integration with metasurfaces, silicon photonics, or 2D materials may yield compact, tunable processors that combine the richness of fiber dynamics with the scalability of integrated platforms. Beyond ELMs, soliton physics offers opportunities to implement optical Ising machines [7], ultrafast optimization solvers, and neuromorphic processors operating at femtosecond timescales (see Figure 2 for a concept illustration). The broadband character of soliton interactions could make them attractive for edge AI in optical communication networks, where computation could be embedded directly into the transmission medium. Furthermore, soliton chaos and noise-resilient states may enable entirely new computing architectures such as stochastic optical processors.

CONCLUSION

Solitons have been a cornerstone of nonlinear optics for five decades. Today, they are re-emerging not only as a subject of fundamental study but as a resource for computing. By bridging nonlinear wave physics with artificial intelligence, soliton-based computing opens a path toward ultrafast, energy-efficient, and noise-robust photonic processors. From long-haul communications to learning machines, solitons continue to find new applications in photonics.

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