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Machine learning and applications in ultrafast photonics

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Recent years have seen the rapid growth and development of the field of smart photonics, where machine-learning algorithms are being matched to optical systems to add new functionalities and to enhance performance. An area where machine learning shows particular potential to accelerate technology is the field of ultrafast photonics — the generation and characterization of light pulses, the study of light–matter interactions on short timescales, and high-speed optical measurements. Our aim here is to highlight a number of specific areas where the promise of machine learning in ultrafast photonics has already been realized, including the design and operation of pulsed lasers, and the characterization and control of ultrafast propagation dynamics. We also consider challenges and future areas of research.

Machine learning is an umbrella term describing the use of statistical techniques and numerical algorithms to carry out tasks without explicit programmed and procedural instructions. Machine-learning algorithms are widely used in many areas of engineering and science, with particular strengths in classification, pattern recognition, prediction, system parameter optimization and the construction of models of complex dynamics from observed data. Machine-learning tools have been widely applied in fields such as control systems, speech processing, neuroscience and computer vision[1].

In optics and photonics, early applications of machine learning have mostly been in the form of genetic algorithms for pattern recognition[2], image reconstruction[3], aberration corrections[4] or the design of optical components[5,6]. More recent work has focused on the analysis of large datasets[7,8] and on inverse problems where the superior ability of machine learning to classify data, to identify hidden structures and to deal with a large number of degrees of freedom have led to many significant results. Particular areas of success include in the design of nanomaterials and structures with specific target properties[9–11], label-free cell classification[12], super-resolution microscopy[13,14], quantum optics[15] and optical communications[16–18].

In addition to applications in the general area of data processing, there is particular potential for machine-learning methods to drive the next generation of ultrafast photonic technologies. This is not only because there is increasing demand for adaptive control and self-tuning of ultrafast lasers, but also because many ultrafast phenomena in photonics are nonlinear and multidimensional, with noise-sensitive dynamics that are extremely challenging to model using conventional methods. While advances in measurement techniques have led to substantial progress in experimental studies of such complex dynamics, recent research has shown how machine-learning algorithms are providing new ways to identify coherent structures within large sets of noisy data, and can even potentially be applied to determining underlying physical models and governing equations based on only the analysis of complex time series.

Our aim here is to review a number of specific areas where the promise of machine learning in ultrafast photonics has already been realized, and to also consider challenges and future directions of study as well as applications where substantial impact is expected in the coming years. Before presenting specific details, we first illustrate in Fig. 1 an overview of different machine-learning strategies and associated architectures, listing the core concepts, implementation methodologies and applications where these have been applied in ultrafast photonics.

Laser design and self-optimization

In this section, we give an overview of the use of machine learning in laser design.

Self-tuning of ultrafast fibre lasers. Ultrafast lasers are essential tools in many areas of photonics, including telecommunications, material processing and biological imaging[19–23]. They have also played a central role in several Nobel prizes awarded for femtosecond coherent control (1999); the development of the precision frequency comb (2005); and, more recently, the generation of high-power femtosecond pulses via chirped pulse amplification (2018). Although some ultrafast sources are based on relatively simple designs, the operation of many important laser systems is in fact very complex, with dynamic pulse shaping determined by the interplay between a range of nonlinear, dispersive and dissipative effects[24]. Although this complexity certainly creates challenges in controlling and optimizing the laser emission, it also offers considerable performance advantage not available with simpler systems. A key challenge is then to harness this complexity.

The difficulty in optimizing a particular ultrafast laser arises from the number of degrees of freedom (or control parameters) that need to be balanced to achieve stable operation or to reach a specific dynamical regime. Of course, efforts to develop self-optimized or autotuned lasers have been made for many years, with the dominant approach being to linearly sweep through a subset of the available parameter space while monitoring the laser output and using a feedback loop to obtain and maintain a desired operating state. While this is a straightforward approach for simpler laser designs with limited parameters, it becomes intractable when the laser operation depends on many degrees of freedom, or when multiple output characteristics need to be optimized simultaneously. Moreover, there is an increasing demand in both research and industrial applications for fully autonomous operation and active realignment in the presence of external perturbations, as well as for the ability to make dynamic changes in pulse characteristics adapted to the

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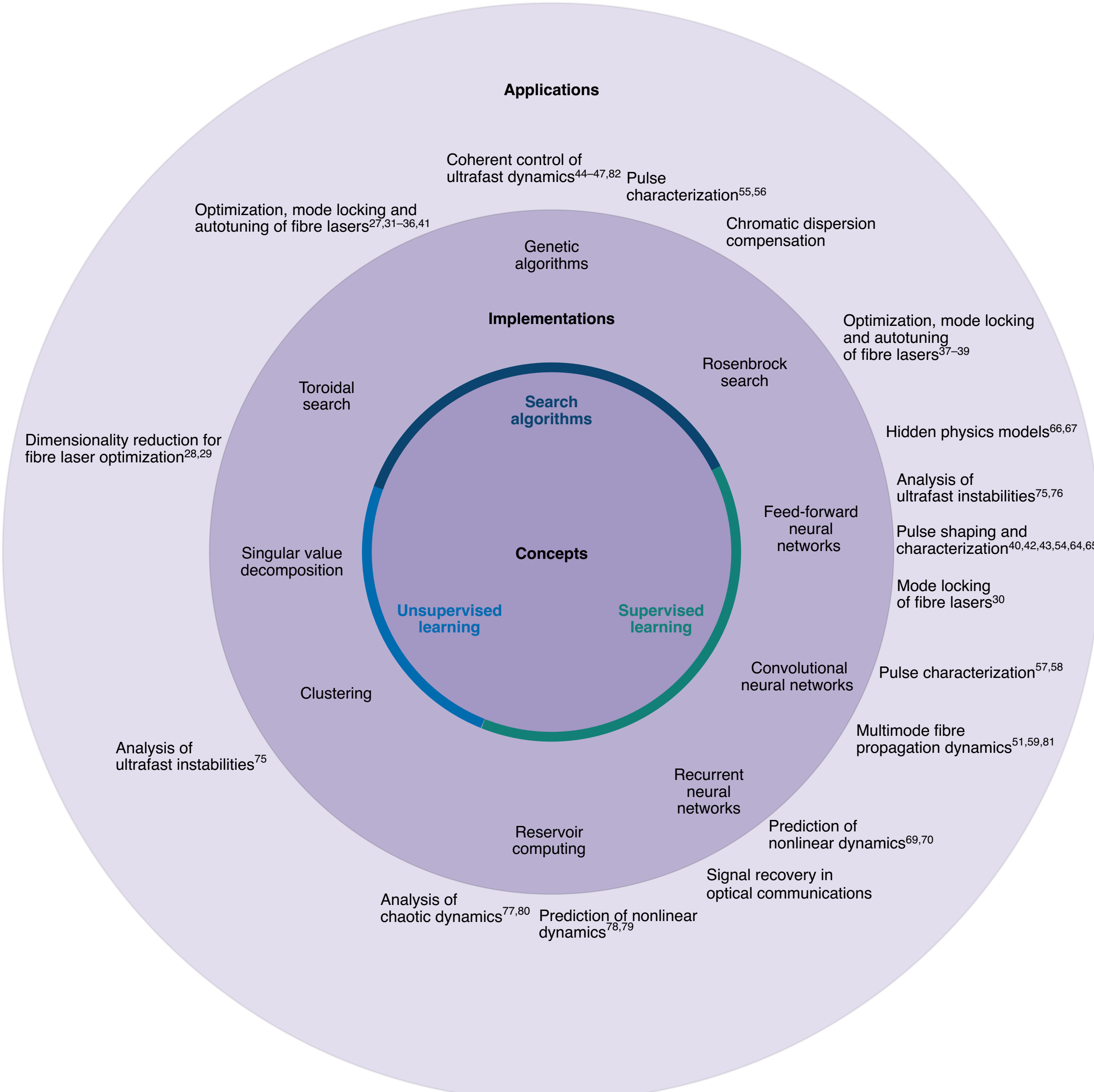


Fig. 1 | Overview of the main machine-learning concepts and implementations that can be used in ultrafast photonics. The figure illustrates the core concepts and corresponding implementation methodologies as delimited by the coloured arcs, and links these to particular applications where these have been applied in ultrafast photonics. There are also other concepts including semi-supervised learning and reinforcement learning, which use some of the implementations mentioned in the figure, but these have yet to be exploited in an ultrafast context. Of course, we also stress that all these methods have been used in many other fields of science in addition to the ones shown here.

target environment (for example, propagation medium or material). It is for such systems with greatly added complexity that approaches based on machine learning are especially promising and desirable.

An important example here is the widespread fibre laser, where polarization control, pump power, spectral filtering and loss combine to create a wide range of possible operating regimes governed by a rich landscape of nonlinear dynamics[25,26]. Depending on the exact choice of parameters, the same laser can exhibit very different behaviour: continuous-wave lasing, noise-like pulse generation, *Q*-switching, mode locking, multiple pulsing and bound states. It is for this multivariable optimization problem where machine learning has recently led to a number of dramatic improvements. The general approach has been to combine an algorithmic feedback loop together with the electronic control of intracavity elements varying polarization, pump power and spectral filtering. Figure 2 shows a generic illustration of machine-learning strategies, control elements and output parameters for optimization of ultrafast fibre lasers. Specifically, Fig. 2a illustrates the training phase where control electronics and advanced measurement devices are used to probe the parameter space and map the corresponding operation states, respectively. Collected data are then fed to machine-learning algorithms for training. Figure 2b shows the self-tuning regime where the operation state of the laser is characterized in real time with a simplified measurement system fed into the machine-learning algorithm controlling the electronics to lock the system to a desired regime. This is where machine learning is particularly powerful as, once trained, the algorithm allows rapid parameter selection for optimum operation. Examples of machine-learning algorithms that can be used are highlighted in Box 1, and general guidelines in applying them are provided in Box 2.

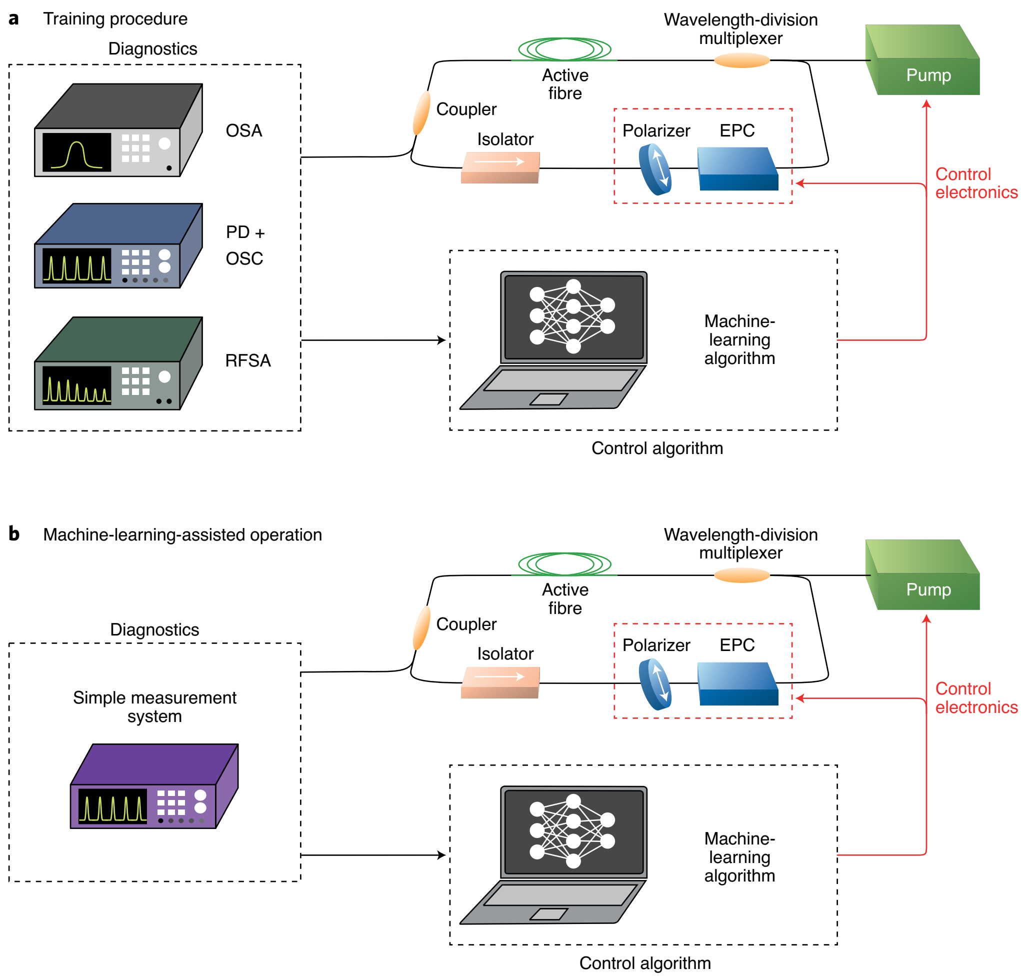


Fig. 2 | Illustration of machine-learning strategies for optimization and self-tuning of ultrafast fibre lasers using control of intracavity elements via a feedback loop and control algorithm. a, Training phase where control electronics acting, for example, on the polarization state (electronic polarization controller (EPC)) sweep the parameter space to map different operating states of the laser to be used as inputs to the control algorithm (Box 1). Guidelines for algorithm and parameter selection are given in Box 2. In the case of a search algorithm, the training phase is not necessary. Output characteristics are measured by diagnostics such as an optical spectrum analyser (OSA), fast photodiode (PD) and oscilloscope (OSC), or radio-frequency spectrum analyser (RFSA), and subsequently used as input to the control algorithm. **b**, Machine-learning-assisted operation where the laser operation is measured in real time and fed into the control algorithm.

Ultrafast fibre lasers mode-locked by nonlinear polarization evolution (NPE) are particularly complex, because a change in the polarization state affects both spectral and temporal pulse shaping, as well as the gain-to-loss balance in the cavity due to the intrinsic saturable absorber role played by the polarization-dependent losses. The first studies combining an algorithmic feedback loop with some cavity control parameter were in fact proof-of-concept numerical simulations of an NPE fibre laser, where it was shown that multipulsing instability could be reduced via filters optimized with a genetic algorithm[27], and that stochastic changes in environmentally induced birefringence could be mitigated by applying a singular value decomposition method[28] or using variational autoencoders on the birefringence state map[29,30]. This modelling was rapidly followed by an experimental implementation using a singular fitness function to identify self-starting regimes in an NPE laser[31]. A number of subsequent experiments for various laser configurations (NPE, ring cavity and figure of eight) have used genetic algorithms to achieve self-tuning and autosetting in different regimes such as Q-switching, mode locking, Q-switched mode locking or the generation of on-demand pulses with different duration and energies[32–36].

Table 1 summarizes a selection of results that have been obtained so far (extended from ref. [37]), also providing the characteristics of the particular algorithms used in each case. In most of these studies, the feedback loop typically uses an advanced search or genetic algorithm targeting a desired optimal state based on some particular fitness or objective function as the reference criterion. Although these results are highly promising, genetic algorithms have to be carefully designed due to their sensitivity to the initial choice of parameters, which can lead the fitness function to converge towards a local optimum. They also cannot accommodate for long-term dependencies, and the fitness function typically monitors a single parameter limiting the operating regime that can be achieved. Another important drawback of genetic algorithms is their relatively slow convergence speed on the scale of minutes or even hours (Table 1). However, recent developments have shown that one can reduce this time considerably using algorithmic modifications that can mimic human logic, with the possibility to lock the laser to a desired operating state and to recover to this state from perturbation in less than one second[38,39]. Further improvement in self-tuning speed is likely to require algorithms that also include models of the pulse-generating mechanism to

Box 1 | Examples of machine-learning algorithms

Genetic algorithms. Genetic algorithms belong to a family of evolutionary algorithms that are inspired by biological evolution. A (random) initial population of genes (system parameters) is first evaluated by a fitness function, and the parents of the next generation are selected according to the fitness score. The reproduction includes a crossover of genes between the parents to create children that may undergo a mutation in which individual genes are randomly altered. Genetic algorithms may also include elitism, where the best individuals are cloned to the next generation.

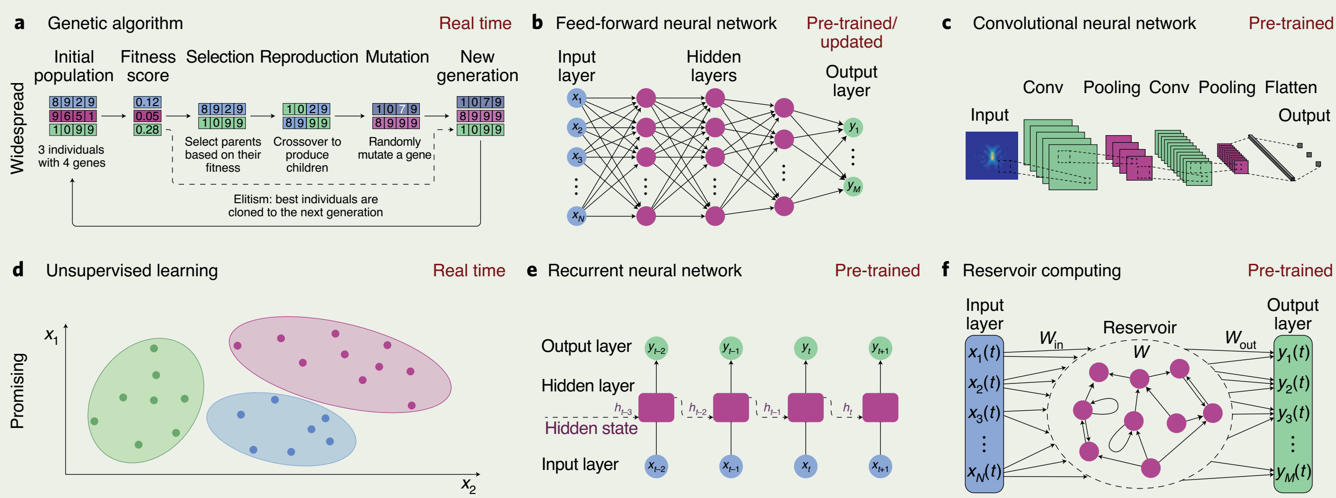
Feed-forward neural networks. Feed-forward neural networks consist of an input layer accepting input data x, multiple hidden layers of basic computational units (neurons or nodes) that perform operations on the data using various weights and a nonlinear activation function, and an output layer that computes the network output y for regression or classification. In feed-forward neural networks, the information flows forward from the input layer through the hidden layers to the output layer.

Convolutional neural networks. Convolutional neural networks are a special type of feed-forward neural network where the input is convolved with a set of filters or kernels, followed by nonlinearity. The resulting feature map is then downsampled by a pooling function reducing the data's dimensionality by combining nearby points into a single value. The convolution and pooling operations can be followed by additional convolutional layers to extract further relevant information from the previous feature maps. The output may then be flattened into a vector form for classification or regression tasks.

Unsupervised learning. This refers to label-free statistical tools for exploratory data analysis without prior knowledge about the data or system. The goals of unsupervised learning techniques typically include finding inherent patterns and structures to partition data into natural groups or clusters according to coordinates (for example, x_1 and x_2), or creating latent variable models for dimensionality reduction and data visualization.

Recurrent neural networks. Recurrent neural networks are a special type of neural network that are used for processing temporal/sequential data. Their topologies include intralayers and nodes with recurrent connections that store the network information from the previous input values. The hidden state of the recurrent nodes h_t is passed on to the next time step such that the output of the recurrent layer y_{t+1} depends on both the new input x_{t+1} and the previous hidden state h_t.

Reservoir computing. Reservoir computing is a particular class of recurrent neural network. In reservoir computing, the input W_{in} and recurrent layer connections W do not participate in the training but instead they are pre-defined in an ad hoc fashion and are often simply drawn from a random distribution. Training only modifies readout weights W_{out} and the usually complex neural network optimization becomes a simple matrix inversion that can be computed in a single step.



Widespread and promising machine-learning architectures for ultrafast photonics. a, Genetic algorithm. **b**, Feed-forward neural network. **c**, Convolutional neural network. **d**, Unsupervised learning. **e**, Recurrent neural network. **f**, Reservoir computing. The different algorithms can be used as indicated: in pre-training before being applied to a particular experimental system, for real-time optimization and tuning, or a combination of both where the algorithm is pre-trained and subsequently updated during system operation.

provide more targeted control. Unfortunately, while models based on nonlinear Schrödinger-like equations (NLSE) are generally able to reproduce experimental characteristics qualitatively, quantitative comparison with experiments remains challenging. This is because accurate modelling necessitates the knowledge of a wide range of parameters that are not readily accessible in practice (for example, the random birefringence in the fibre). Ultrafast lasers are also stochastic systems and the impact of noise can generally be reproduced via only computationally intensive Monte Carlo simulations that require the analysis of a very large amount of data. One can anticipate that the use of machine-learning techniques for pattern recognition combined with the latest advances in real-time measurement techniques[40,41] could lead to better understanding of ultrafast laser dynamics, allowing for the construction of laser systems with improved robustness.

Control of coherent dynamics. In addition to directly controlling laser emission as described above, there is widespread use of extra-cavity shaping technology to modify the characteristics of ultrashort pulses and other light sources used in particular applications. Because such optimization can involve multiple parameters that are interconnected in complex ways, this is an area where machine learning can clearly surpass other forms of manual or partially automatized control.

Box 2 | General considerations when applying machine-learning models

Choosing an architecture and associated parameters. Neural networks are universal function approximators whose performance significantly depends on their hyperparameters (variables that determine the network structure and training). Selecting the optimum architecture (Fig. 1 and Box 1) and tuning the hyperparameters often involves significant heuristics, exhaustive scans, trial and error, and leveraged optimization tools (genetic algorithms[99,100] or Bayesian methods[101,102]). Nevertheless, one may consider the following guidelines to select an appropriate architecture and hyperparameters: a feed-forward neural network is a good choice if the map from input to output lacks temporal context. This is typically the case when one considers input–output mappings of 'single pass' systems such as pulses undergoing nonlinear propagation, where fluctuations are expected to be independent and uncorrelated, and also for particular classes of similarly (partially) uncorrelated instabilities in *Q*-switched lasers. If data contain structure along a particular input dimension (for example, space, time or wavelength), architectures including filters such as convolutional neural networks are better candidates; one may employ fully connected topologies for input data apparently lacking such features. If the output is expected to depend on current and past input data, recurrent topologies (long short-term memory, gated recurrent units or reservoir computing) should be used.

Accuracy generally increases with the number of hidden layers or nodes. The number of layers, nodes and training epochs can be increased until the validation error starts increasing (even if the training error still decreases). Note that too many nodes can lead to overfitting and reduce generalization (the ability of a trained model to adapt accurately to data outside the initial training dataset). Continuously reducing the number of nodes for deeper layers is a common strategy to improve generalization, and two to three hidden layers comprising 50 to 1,000 nodes seem sufficient for most tasks in ultrafast photonics. A neural network's inference quality is quantified by a cost function such as mean-squared or root-mean-squared error. The root-mean-squared error penalizes small divergences more heavily and can be employed when fast and accurate convergence is essential. Network weights are typically initialized randomly, and popular activation functions are the rectified linear unit and the sigmoid nonlinearity. The rectified linear unit is computationally less expensive and avoids vanishing gradients, while the sigmoid's upper limit makes blowing-up solutions less likely.

Selecting training data. There is generally no one-size-fits-all criterion to determine the volume of training data needed for a specific network and task. Where possible, one can be guided by available examples of comparable problems, and more generally, an initial guess can be obtained by considering the number of classes (output neurons), relevant input features (for example, optical modes) and parameters of the underlying model. One can then continuously increase the volume of training data until the validation error stagnates. The training data should be representative of the system's possible states, and therefore sample uniformly the system's phase space. This can be challenging, especially for ultrafast nonlinear systems, which may rarely visit specific outlier regions (so-called skewed dataset), and can lead to degraded performance in testing. Feeding representative datasets is also not always possible during experiments, and data augmentation via simulation is an alternative approach. It is also important to normalize training data to the 'useful' range of the neurons' nonlinear response (around unity) to prevent the network operating in the linear or saturated regime.

Avoiding overfitting. Unlike in genetic algorithms, overfitting can occur in neural networks, typically when the testing error is large compared with the training error. The risk of overfitting may be reduced using the following strategies: simplification to reduce the network complexity; data augmentation by increasing the fraction of noisy data during training; cross-validation where division of data into training and testing sets is varied during training; early stopping where training is stopped when the testing error starts increasing; regularization by including penalties in the system's loss function; drop-out by randomly removing individual connections during training.

Robustness and transfer learning. Ultrafast photonics systems are generally sensitive to their environment. Enabling stable and robust operation is another key objective for machine learning. Performance degradation upon a change of environmental conditions will mostly depend on the parameter space and regimes explored during training and testing. It is therefore important to include training data that incorporate possible environmental variations (see also 'Selecting training data'). Using unsupervised learning to determine the dynamic relation between external conditions and system output is another approach.

A related question is 'transfer learning', or how a neural network architecture optimized for a particular system can be 'transferred' to a different yet related problem. In particular, the output of an ultrafast system can be divided into different regimes depending on the system parameters. This is particularly true for mode-locked laser pulses, which typically correspond to fundamental solitons, dissipative solitons or periodic breathers depending on the laser dispersion, nonlinearity, gain, loss and filtering. Transfer learning may then use training data generated with simplified mathematical models[103] or experiments with reduced complexity. In fact, transfer learning is in itself an important topic of machine-learning research and from that point of view, ultrafast photonic devices could be ideal testbeds for investigating transfer learning problems in general.

For example, pulse compression to a transform-limited duration is essential to femtosecond spectroscopy that uses few-cycle laser pulses to probe physical or chemical interactions. Recently, it has been shown how an adaptive neural network algorithm can control a pulse shaper and accelerate significantly the compression implementation with a convergence speed 100 times faster than that obtained using more conventional evolutionary algorithms (Fig. 3a)[42]. Similarly, a neural network was used to determine and optimize the parameters of a pulse-shaping system composed of a series of dispersive and nonlinear fibre elements to generate arbitrary pulse waveforms (parabolic, triangular or rectangular) of desired duration and chirp[43].

Genetic algorithms can also be used for these purposes, and their application to solve highly nonlinear optimization problems such as fibre supercontinuum generation has also been very successful[44–47]. Using custom pulse-train preparation via an integrated pulse-splitter, a genetic algorithm was used to optimize supercontinuum dynamics to maximize spectral intensity in specific wavelength bands[47] (Fig. 3b). In another study, it has been shown how Gaussian-like peaks could be generated at desired wavelengths in a supercontinuum spectrum using a genetic algorithm to tailor the spectral phase of the incident ultrashort pulses[46]. Genetic algorithms have also been applied to the design

Table 1 | Comparison of machine-learning tuning approaches in ultrafast fibre lasers

Laser system	Control element(s)	Fitness function(s)	Type of algorithm(s)	Targeted regime/ parameters	Advantages	Disadvantages	Speed
NPE fibre laser[38,39,41]	Electrical polarization controller	Different for different regimes	Rosenbrock search algorithm, random collision recovery, genetic algorithm	Fundamental and harmonic mode locking, *Q*-switching and *Q*-switched mode locking	Versatile, real time, various regimes of operation	Limitations of real-time techniques to detect all classes of laser instability	Average mode-locking time of a few seconds, subsecond recovery time
Figure-of-eight laser[40]	Pump diode powers	Pulse (autocorrelation) duration based on nonlinear fibre DFT measurements	Feed-forward neural network, XGBoost, linear regression	Replace time domain comb, radio-frequency spectrum and DFT measurements by a single measurement tool	Real-time multiparameter monitoring with a single oscilloscope	Requires a large number of measured parameters	Not available
Mode-locked fibre laser[30]	Waveplates, polarizer	Pulse energy divided by spectral kurtosis of the waveform	Recurrent neural network, variational autoencoder with latent variable mapping (feed-forward neural network)	Stable mode locking	Fast recovery from changes in the fibre birefringence	Complex and rather slow training process	Numerical results
NPE fibre laser[35]	Liquid-crystal-based electrical polarization controller	Radio-frequency power at expected repetition rate, spectral similarity and output power	Genetic algorithm	Stable mode locking	Output spectra can be tuned	Only fundamental mode locking	Initial mode-locking time of 90 s, 30 s recovery time
Ring fibre laser[34]	Electronic polarization controller, pump power	Centre wavelength and repetition rate	Genetic algorithm	Stable and tunable *Q*-switching	Tunable centre wavelength and repetition rate	Limited tuning range of around 20 nm	Not available
NPE fibre laser[32]	Polarization controller	Modified amplitude of the *n*th harmonic in radio-frequency spectrum	Evolutionary algorithm	Harmonic mode-locking regime with anomalous dispersion	Optimized for high-harmonic mode locking	Slow convergence	Harmonic mode-locking time of 2 h
Figure-of-eight laser[33]	Electronic polarization controller, pump power	Peak power, maximized radio-frequency signal at fundamental frequency, and spectral bandwidth	Genetic algorithm	Anomalous dispersion with NALM for stable single-pulse mode locking	High contrast between stable and unstable pulsing regimes	Complex fitness function, slow convergence	~30 min
NPE fibre laser[31]	Electrical polarization controller	Second-harmonic power for anomalous dispersion operation, intensity of FSR radio-frequency component for normal dispersion	Evolutionary algorithm	*Q*-switched mode locking and stable mode locking	Two regimes of operation	Slow convergence	~30 min
Mode-locked fibre laser[28,29]	Polarizer, waveplates	Pulse energy divided by spectral kurtosis of waveform	Toroidal search algorithm and singular value decomposition, sparse search algorithm, extremum-seeking control	Stable mode locking	Library of identified birefringence states can be used for fast identification of unknown birefringence and optimal controller parameters	Library of all possible birefringence states must be built	Numerical results, few to tens of minutes to build the library
NPE fibre laser[27]	Waveplates, polarizers, amplifier and gain	Pulse energy of single pulse solution	Genetic algorithm	High-pulse-energy mode locking without multipulsing instabilities	Simple fitness function	Requires complex polarization control	Numerical results

DFT, dispersive Fourier transform; FSR, free spectral range; NALM, nonlinear amplifying loop mirror.

of fibres with optimized dispersion and nonlinearity coefficient to maximize the bandwidth of the coherent supercontinuum in the mid-infrared[44].

Ultrafast characterization. A central element in the application of machine learning to tune an ultrafast laser is the feedback loop coupling the emitted pulses with the laser cavity parameters. Although some success has been obtained through optimization based on measurements of pulse spectra or temporal autocorrelation functions, ideally a feedback signal based on more complete pulse measurements would be desirable. However, such complete pulse characterization on femtosecond and picosecond timescales generally requires complex optical systems, and the retrieval of the field parameters is an inverse problem which can be particularly time consuming to solve[48].

Recently, deep neural networks have found applications in solving such inverse problems in areas such as coherent imaging[49,50], imaging through scattering media[51,52] or super-resolution[53], and they are now also showing great promise in pulse reconstruction. The first attempt to apply a neural network to reconstruct a short pulse actually dates back to the mid-1990s and the first development of frequency-resolved optical gating (FROG)[54], although this was limited in making strong assumptions about the functional form of the pulse being retrieved. In other work, genetic algorithms have also been successfully applied to FROG trace retrieval[55,56], but pulse retrieval times still took several minutes. More recently, a convolutional network trained on simulated data was used to reconstruct pulses from experimental FROG traces and was shown to be superior to conventional methods even in the presence of high noise (Fig. 3c)[57]. Additional studies have employed convolutional networks to reconstruct pulses from dispersion scan traces[58], or from multimode fibre nonlinear speckle measurements[59]. Phase recovery for image reconstruction[60–63] and X-ray pulse characterization[64,65] are also among important emerging and growing areas of applications of machine-learning techniques.

Complex dynamics and transient instabilities

In this section, we review the application of machine learning to the control and characterization of ultrafast propagation dynamics.

Hidden physics models. The application of machine learning to derive predictive models from sparse or noisy measurements has now penetrated research into the study of the basic properties of physical systems. In particular, a new field of 'hidden physics models' has arisen where closed-form mathematical models or nonlinear differential equations governing a physical system[66] are identified automatically by analysing samples of the dynamical data using 'physics-informed neural networks'. In some cases, the form of the governing equation(s) may be known or assumed in advance, and the goal is to extract only the unknown coefficients[67]. Alternatively, one can combine a neural network with a compressed sensing-like method to identify only the active terms of the equation(s) from a basis of candidate nonlinear functions[68].

Using these approaches, a number of applications in ultrafast photonics have been demonstrated to analyse pulse propagation dynamics in optical fibre or in fibre lasers associated with the generation of localized and dissipative soliton structures (Fig. 3d)[67]. Model-free approaches in the form of reservoir computing (unlike physics-informed neural networks) have also been implemented to predict coherent dynamics in particular cases of soliton-like propagation (Fig. 3d)[69]. At present, however, such work has been based on numerical data only — the next step in this field is clearly to uncover the governing models from experimental datasets.

Another important area of work involves the study of temporal dependencies observed in nonlinear pulse propagation dynamics, where the temporal and spectral intensity profiles at a specific time instant or propagation length depend on the intensity profiles at earlier times or distance. Recurrent neural networks with internal memory (which are traditionally used for processing and predictions of time series) are particularly well suited to modelling this type of dynamic behaviour. Indeed, very recent results exploiting the memory capacity of recurrent neural networks show how a recurrent neural network with a long short-term memory cell architecture can accurately predict the nonlinear propagation dynamics of short pulses for a wide range of scenarios from higher-order soliton compression (where comparison was made with experiment) to octave-spanning supercontinuum generation[70]. In addition to these studies of single-pass nonlinear propagation dynamics, there is clear potential to use recurrent neural networks in predictions of the complex multiscale intermittence dynamics also seen in optical fibre lasers[71].

Chaotic systems and instabilities. Chaotic modulation instability in NLSE-like systems is one of the most fundamental examples of instability in optics, with analogues in many other physical systems. Indeed, the study of how incoherent noise can 'self-organize' within the NLSE to yield coherent breather structures has attracted wide interest, specifically because of possible links with rogue waves and extreme events[72]. However, the complexity of the measurement techniques needed to directly capture such chaotic breathers on ultrafast timescales has imposed severe constraints on the dynamical regimes that can be explored in experiments[73,74].

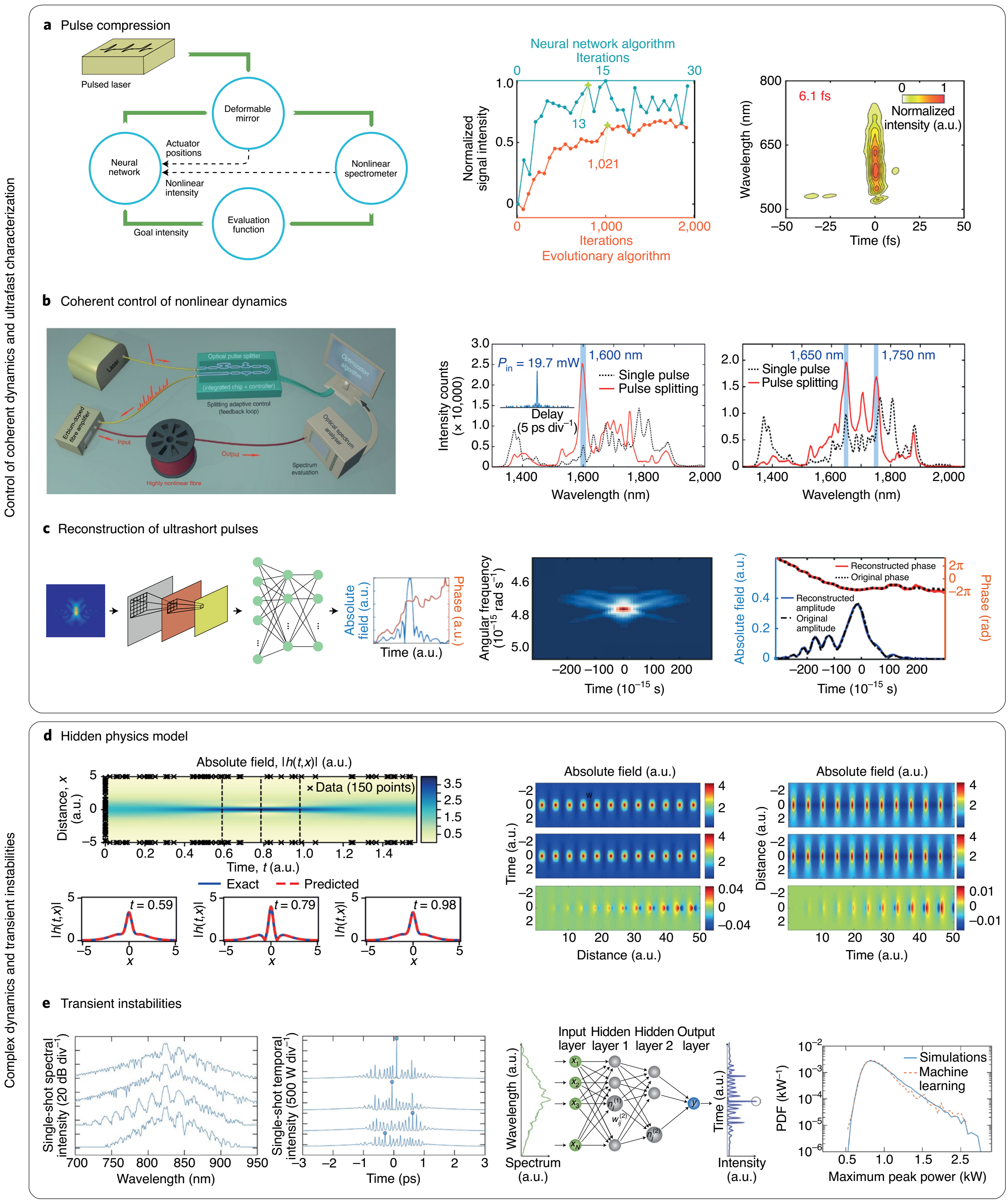
Machine learning has been used to address this problem directly by training a neural network to determine the temporal characteristics of a chaotic field based on only the spectral intensity characteristics (which are easier to measure). Using numerical data generated from NLSE simulations, a neural network was used to construct a nonlinear transfer function that maps noisy broadband spectra to the local intensity maximum of the chaotic temporal field (Fig. 3e). This function was then applied to experimental data measured using a high-dynamic-range real-time spectrometer[75]. A similar approach was recently used to determine the peak power, duration and temporal delay of extreme rogue solitons in noisy supercontinuum generation[76]. In addition, analysing chaotic data from modulation instability, unsupervised clustering analysis using the *k*-mean algorithm was shown to successfully sort intensity spectra into subclasses associated in the time domain with specific solutions of the NLSE related to analytic soliton structures[75].

The application of machine-learning techniques has been extended to even more complex systems such as those observed in transient laser behaviour and extreme events[77]. Specifically, using the knowledge of previous pulses in a chaotic time series from an optically injected semiconductor laser, machine-learning methods

Fig. 3 | Machine-learning applications in ultrafast photonics. a, Pulse compression. Left: optimization procedure. Middle: convergence comparison between neural network and evolutionary algorithm. Right: compressed pulse FROG. **b**, Controlled nonlinear propagation. Left: schematic. Right: examples of customized supercontinuum spectra. P_{in} is the average power of the optimized pulse train leading to maximum spectral intensity at selected wavelengths corresponding to the blue shaded regions. **c**, Pulse reconstruction using a convolution neural network. Left: architecture. Middle: reconstructed FROG. Right: reconstructed pulse. **d**, NLSE solution using a neural network. Left: pulse evolution (top) and comparison of predicted and exact solutions (bottom) at three particular points (dashed lines). Right: Kuznetsov–Ma (left) and Akhmediev breather (right) dynamics showing expected evolution (top), predicted evolution (middle) and relative difference (bottom). All colour bars are in normalized units. **e**, Modulation instability. Left: simulated spectra (network input; left) and temporal profiles (network output; right). Middle: network schematic for correlation of spectral and temporal characteristics. Right: probability density function (PDF) of predicted temporal intensity based on experimental spectra (dashed red line) compared with simulated PDF (blue line). Figure adapted with permission from: **a**, ref. 42, **c**, ref. 57, OSA; **b**, ref. 47, **d**, right, ref. 69, **e**, ref. 75, under a Creative Commons licence (https://creativecommons.org/licenses/by/4.0/); **d**, left, ref. 67, Elsevier.

(nearest neighbours, support vector machine, feed-forward neural network and reservoir computing) were analysed for their ability to predict the intensity of upcoming pulses emitted from the laser[77,78]. Although this work was numerical, it clearly shows the potential of such prediction for experiment. Attempts have also been made to model highly incoherent system evolution, including multidimensional spatiotemporal systems[79], but the predictions in this case tend to diverge over longer distances[80].

Multidimensional systems. A major benefit of neural networks is their ability to efficiently analyse the properties of multidimensional systems. This can be particularly useful in multimode fibre



systems where spatiotemporal coupling dramatically increases the parameter space and complexity of nonlinear propagation dynamics. The potential of machine learning in this case was recently demonstrated with experiments tailoring supercontinuum generation in a graded-index fibre through control of the injected spatial beam profile via a neural-network-driven spatial light modulator[81].

Extension to spatial control for enhanced near-field interactions was also shown by combining a neural network with a genetic algorithm to optimize spectral-phase shaping of an incident field to achieve second harmonic generation hotspot switching in plasmonic nanoantennas[82]. In this latter work, the genetic algorithm was added to generate a wide range of nanoantenna designs to be fed into the neural network.

Outlook and challenges

Ultrafast photonic systems are generally very complex, often nonlinear, and with dynamics extremely sensitive to both their internal parameters and external perturbations. The design and optimization of these systems have been typically based on physical models, numerical simulations and trial-and-error approaches. With the increased complexity of these systems, driven by the demand for high stability, robustness against disturbances, tunability and adaptive control, these approaches are now starting to reach their limits such that future major advances will require new methodologies that can analyse the system characteristics at a global level. One may therefore anticipate that machine-learning techniques able to discover hidden features and independently adapt as they are exposed to new data are likely to play a central role in the next generation of ultrafast systems and applications. There are of course many ways machine-learning techniques can be exploited, and we discuss below some possible future directions of research and challenges to overcome.

Ultrafast fibre lasers are dynamical systems operating in regimes determined by dispersion, nonlinearity, gain, losses and saturation effects. Optimization, breakthrough performance, high stability against perturbations and automatic tuning requires in-depth understanding of the full system parameter space, which can be achieved by combining accurate real-time characterization and advanced data analysis. Machine-learning-based approaches have the potential to reduce the complexity and number of measurement devices typically required. They could further allow for converting results of measurements into a higher-dimensional space where the separation of the role played by the different cavity elements is more apparent, aiding the construction of universal models. Machine learning may also yield substantial developments in full and high-speed characterization of short pulses or complex fields arising from highly nonlinear dynamics. Adaptive optics and coherent control typically rely on ultrafast laser systems where the spatial, temporal and spectral properties of the laser beam are central to optimum performance in, for example, metrology[83], spectroscopy[84,85], energy harvesting[86] or astronomy[87]. By enabling more systematic strategies rather than heuristic approaches (for example, in the optimization of multidimensional systems including beam shaping and spacetime focusing in multimode fibres[88–90]), machine learning could enable unprecedented level of control in those applications. Another important area where we expect machine learning to lead to substantial progress is the discovery of models using data-driven strategies to identify governing mathematical equations of complex optical phenomena or photonic systems. It is even conceivable that in the future, ultrafast fibre lasers could become testbeds for the physics discovered from machine learning.

So far, most machine-learning applications to ultrafast photonics have been based on genetic algorithms or feed-forward architectures. While these implementations have undoubtedly led to remarkable and pioneering results, there are still important approaches that have yet to be fully exploited. Indeed, it is likely that realizing the full potential of machine learning will necessitate the combination of several strategies that have so far been used only separately. For example, recurrent networks based on long short-term memory cells, gated recurrent units or reservoir computing that possess internal memory can be used to model dynamical systems consisting of time series of different states. These approaches could enable substantial progress in understanding and optimizing nonlinear systems, allowing identification of long-term dependencies and internal dynamics in ultrafast lasers, or the prediction of complex evolution maps associated with the propagation of short pulses in nonlinear media and related instabilities. Also, the capabilities of unsupervised learning to draw inferences and reveal hidden internal structures from datasets without labelled responses could be of significant interest in problems where dimensionality reduction is key. These include, for example, multimodal systems or noise-sensitive dynamics where specific regimes can be divided into a number of different clusters associated with measurable parameter(s). Moreover, approaches employed for the design of nanophotonic components in the form of machine learning combined with the adjoint method[91] could be a powerful tool for the inverse design of ultrafast photonics systems. The concept of generative adversarial networks[92] where two distinct networks are optimized in the backpropagation operation[93] is another promising avenue to explore in ultrafast photonics.

There are of course important challenges ahead. When using a recurrent network to analyse and predict dynamics, proper sampling along the evolution dimension (time or distance) is essential to extract and reproduce the long-term evolution structure. Memory limitations can then become an issue, especially in the context of lasers where it takes usually many cavity round trips for a regime to stabilize. Unsupervised learning analysis divides the data into subsets with similarities, but crucial information on the criterion used to perform the division, or on what the similarities actually are within the clusters is lacking. This means that to fully exploit the power of unsupervised learning, further human investigation is generally needed to establish the link between the clusters and specific parameters of the system analysed. This can be a limiting factor, especially for the case of noise-sensitive systems where tiny variations can result in dramatically different evolution patterns.

The use of machine-learning algorithms for real-time processing of photonic systems that can produce data in excess of billions of bits per second requires the ability to manage high data volumes, as well as a hardware framework capable of dealing with ultrafast processing rates. To reduce the large volume of data, one could use the approach of spike-based neural networks that can reconstruct features of spatiotemporal states based on analysing only a subset of the measured data. Inspired by the human brain, which strongly compresses the information received from the eye[94], spike-based neural networks use a specific set of rules such as spike time-dependent plasticity leading to self-organization of the network's topology and allowing identification of possible correlations in the input data. When combined with lateral inhibition (a spike-based form of a winner-take-all topology), spiked-based neural networks can self-configure to perform a cluster analysis with performance similar to that achieved with a *k*-mean algorithm[95]. Efforts to develop a hardware framework allowing for high-speed processing and optimization on short timescales have already been made, and several all-optical network architectures have been proposed based on, for example, multiple layers of diffractive surfaces where each point on a given layer acts as a node[96], or optical matrix multiplication using a cascaded array of Mach–Zehnder interferometers integrated into a silicon photonic circuit[97]. Another promising approach could be to combine all-optical field-programmable gate arrays and fully parallel photonic neural network hardware. Of course, one important constraint to the development of all-optical neural networks that needs to be carefully studied is the tolerance to photonic component fabrication imperfections[98].

In the past few years, there have been remarkable developments enabled by the use of machine-learning techniques, and an active field of machine-learning ultrafast photonics has now been established. As research continues to progress both in the development of machine-learning algorithms and ultrafast photonics technologies, we can expect even more fruitful interactions with increased influence of the former in the physical understanding, design, optimization and operation of the latter.

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Competing interests

The authors declare no competing interests.

Additional information

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