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Nonlinear Sculpturing of Optical Pulses in Fibre Systems

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INTRODUCTION

In recent years, there has been a growing interest from the photonics community in the generation of non-conventional optical waveforms because of their applications in all-optical signal processing and microwave signal manipulation. While sinusoidal, Gaussian and hyperbolic secant intensity profiles are now routinely produced by modulators or mode-locked lasers, other signal waveforms such as parabolic, triangular or flat-top pulse shapes remain rather hard to synthesize. The interplay among the effects of dispersion, nonlinearity and gain/loss in optical fibre systems can be efficiently used to shape the pulses and manipulate and control the light dynamics and, hence, lead to different pulse-shaping regimes. In particular, it has been demonstrated that the temporal and spectral properties of a pulse can be tailored by use of such a nonlinear shaping approach to generate ultra-short parabolic or triangular pulses [1, 2].

However, achieving a precise waveform with various prescribed characteristics, such as temporal duration and chirp properties, is a complex issue that requires careful choice of the initial pulse conditions and system parameters. The general problem of optimization towards a target operational regime in a complex multi-parameter space can be intelligently addressed by implementing machine-learning strategies. In this paper, we discuss a novel approach to the characterization and optimization of nonlinear shaping in fibre systems, in which first we perform numerical simulations of the basic propagation model to identify the relevant parameters, and then we use the machine-learning method of neural networks (NNs) to make predictions across a larger range of the data domain.

IN PASSIVE NORMALLY DISPERSIVE FIBER

NUMERICAL MODEL

➤ Propagation in normally dispersive fiber is governed by the nonlinear Schrödinger equation (NLSE) :

$$i \frac{\partial \psi}{\partial z} - \frac{\beta_2}{2} \frac{\partial^2 \psi}{\partial t^2} + \gamma |\psi|^2 \psi = 0$$

group velocity dispersion Kerr nonlinearity

➤ 6 degrees of freedom : $(C_0, T_0, P_0, \beta_2, \gamma, L)$
input pulse fibre

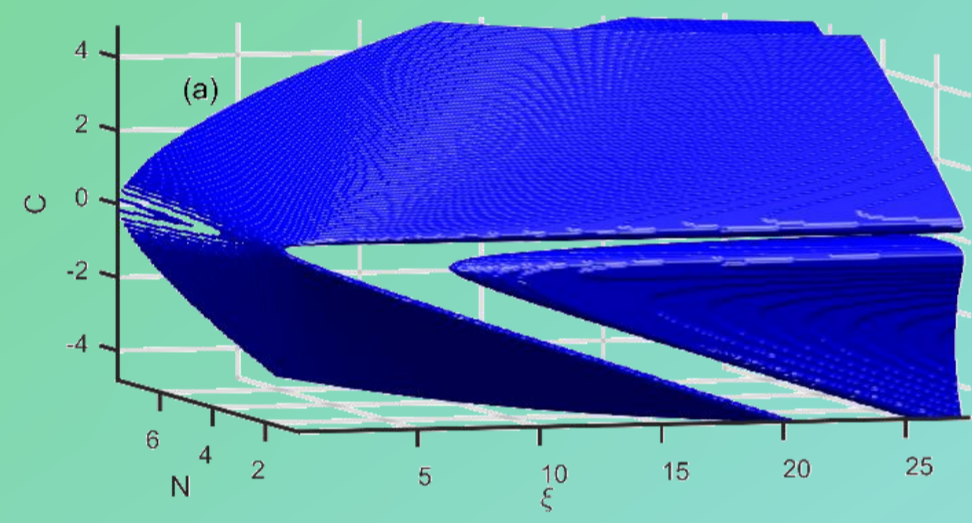
➤ Using normalized quantities reduces the level of complexity.

(C, N, ξ) : normalized input chirp, soliton number, normalized propagation length

$$i \frac{\partial u}{\partial \xi} - \frac{1}{2} \frac{\partial^2 u}{\partial \tau^2} + N^2 |u|^2 u = 0$$

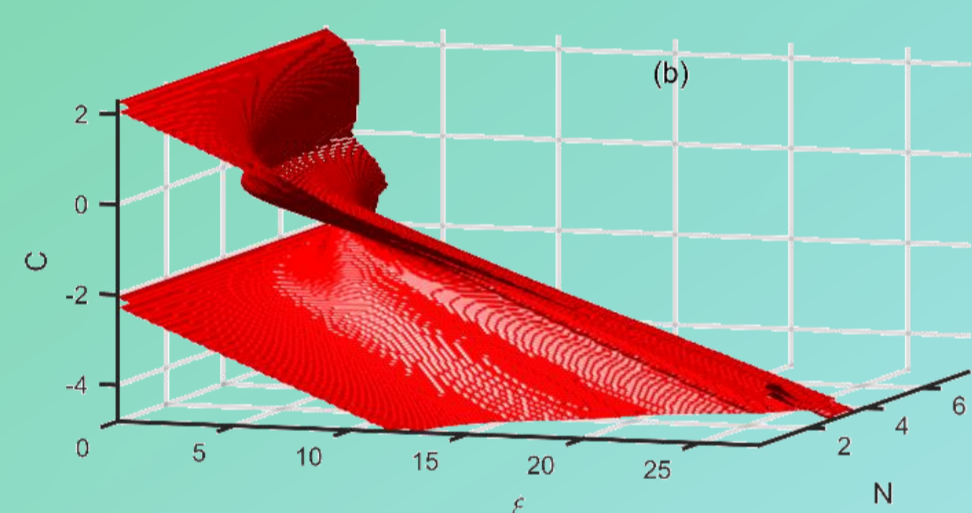
➤ Output pulse properties are quantified using the full-width at half maximum temporal and spectral widths, the Strehl ratio, a misfit factor or the kurtosis excess.

SEARCH FOR THE OPTIMUM WORKING PARAMETERS

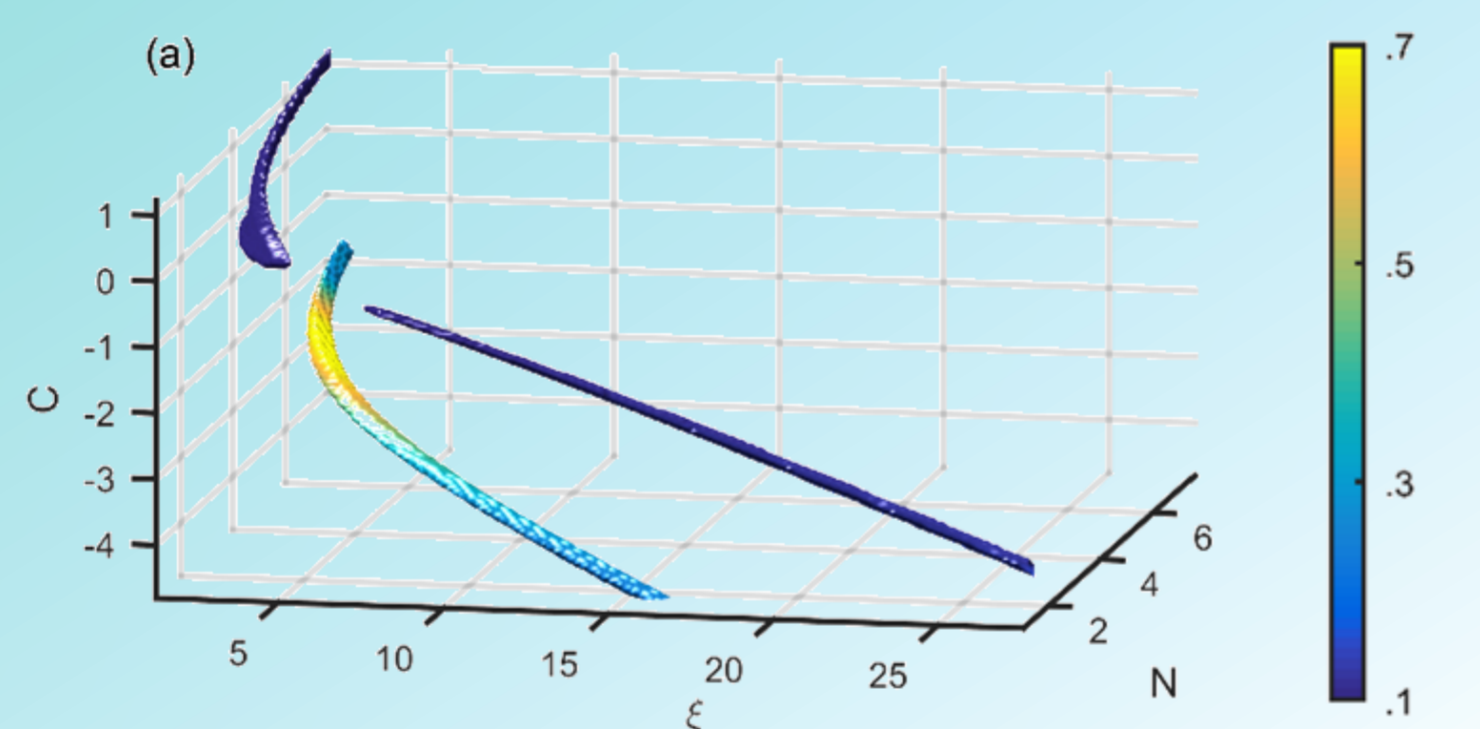


➤ The three-dimensional space of normalized quantities can be visualized using 3D plots.

Surfaces in the three-dimensional parameter space that enable:
 (a) the formation of a pulse with a misfit parameter to a parabolic shape $M \leq 0.045$
 (b) an output temporal duration of $T_{out} = 10 T_{in}$

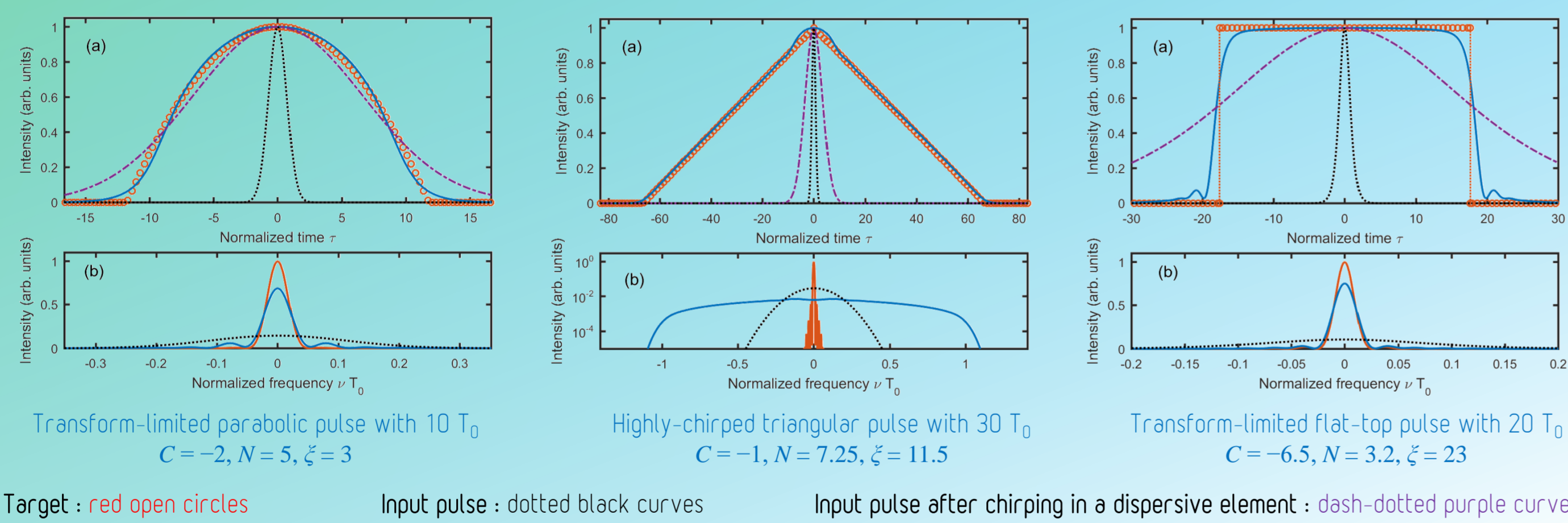


➤ The intersections of different surfaces provide the means to quickly identify the sets of parameters of interest.

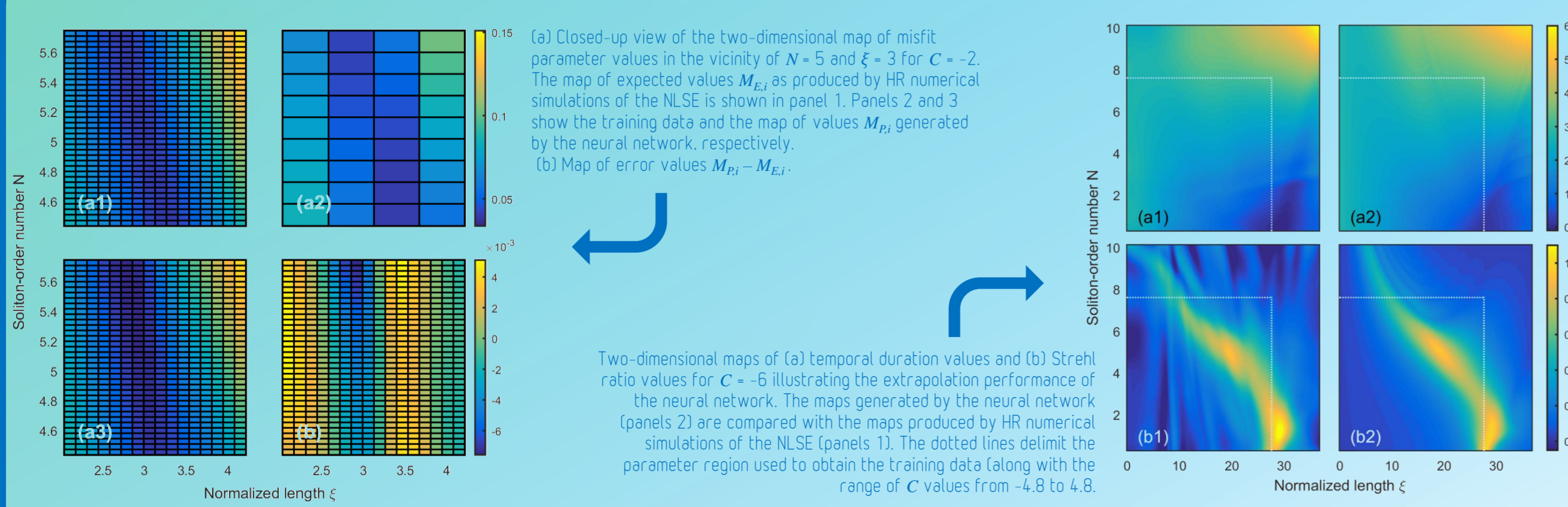


Crossings of parameter surfaces supporting the formation of a parabolic waveform with duration of $10 T_{in}$. The color map indicates the Strehl ratio's values of the resulting pulses.

EXAMPLES OF RESULTS



NEURAL-NETWORK TRAINING

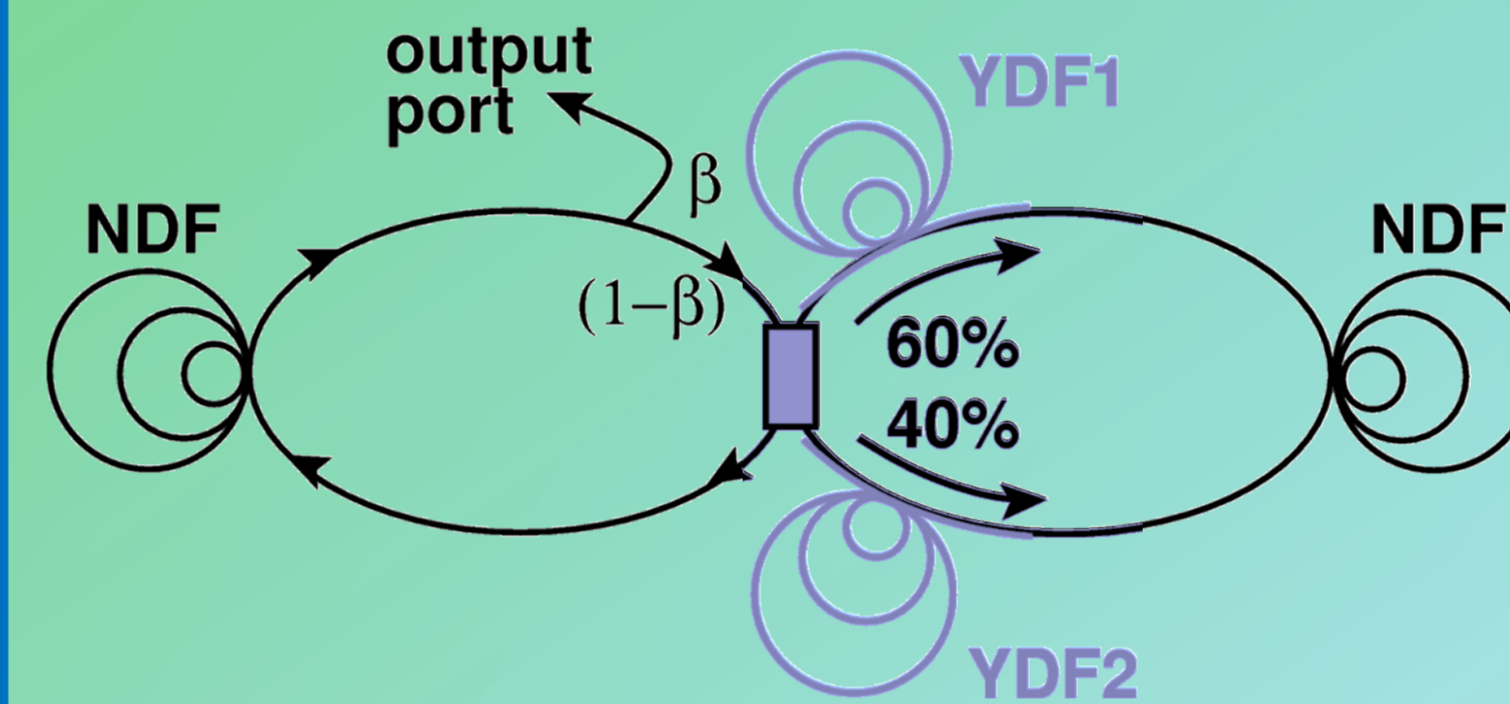


- A NN regression can reproduce the observed trends.
- The reduced-size data set used to train the NN enables a reduction of the CPU time by a factor of 16 relative to the generation of the full data set.
- The predictions from the NN are found to be sufficiently accurate for the targeted application.

IN A DUAL-PUMP NONLINEAR AMPLIFYING LOOP MIRROR MODE-LOCKED ALL-FIBRE LASER

NUMERICAL MODEL

➤ We numerically characterize the performance of the figure-8 laser demonstrated in [4], based on a dual-pump nonlinear amplifying loop mirror.



- two segments of ytterbium doped fibre are used.
- normally dispersive fibres are included.
- the output coupling ratio can be changed.

➤ We use a lumped model for the laser, in which propagation in the fibres follows a generalized NLSE:

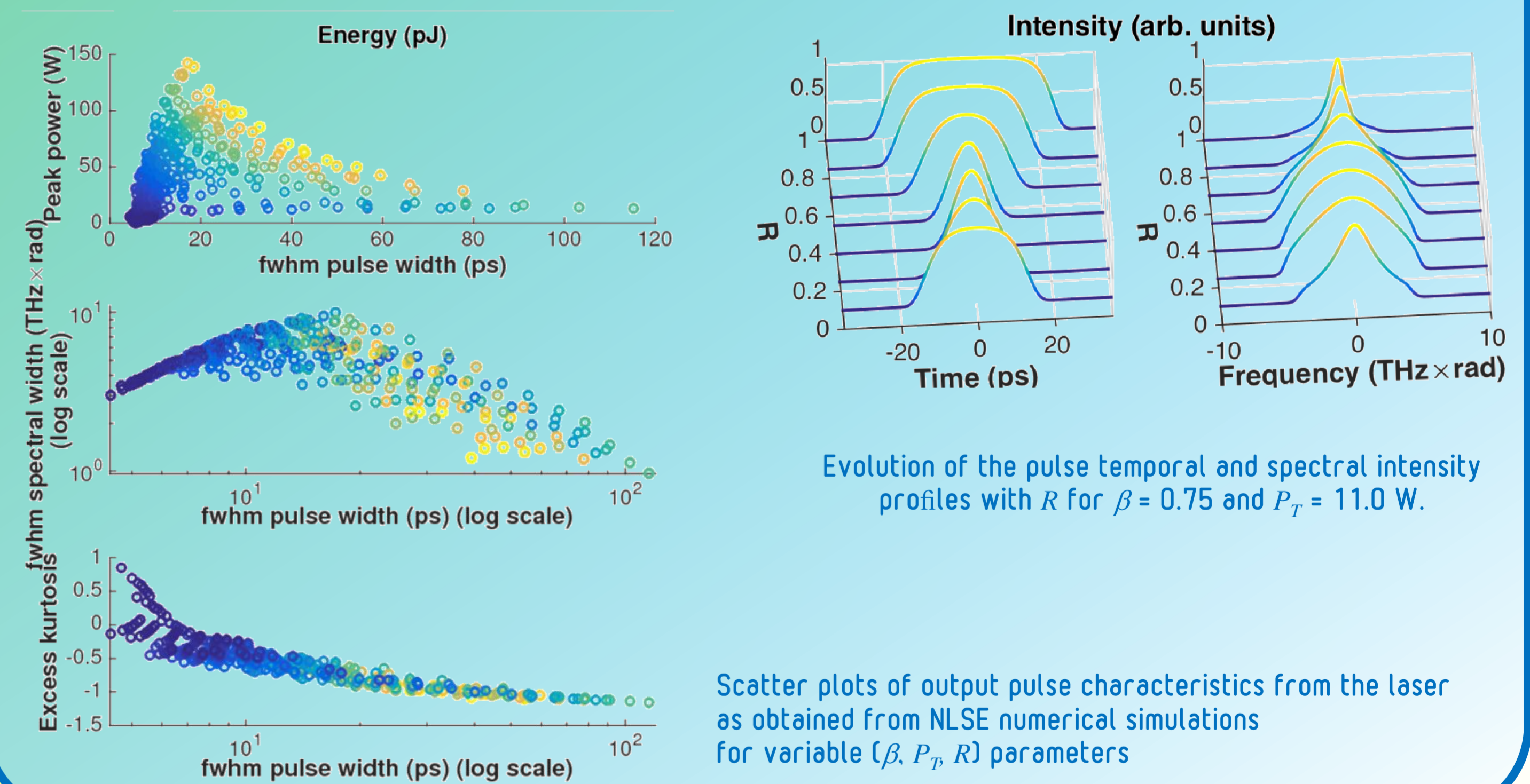
$$i \psi_z - \frac{1}{2} \beta_2 \psi_{tt} + \gamma |\psi|^2 \psi = \frac{i}{2} g(z, \omega) \psi$$

The gain g includes saturation and spectral response

- Due to the longitudinal evolution of g (requiring the solution of steady-state rate equations for an effective two-level system at each longitudinal step), direct simulations are time consuming.
- We explore the space of operating states that can be accessed through control of the total pump power $P_T = P_1 + P_2$, the fractional pump power $R = P_1/P_T$ and the laser output coupling ratio β .

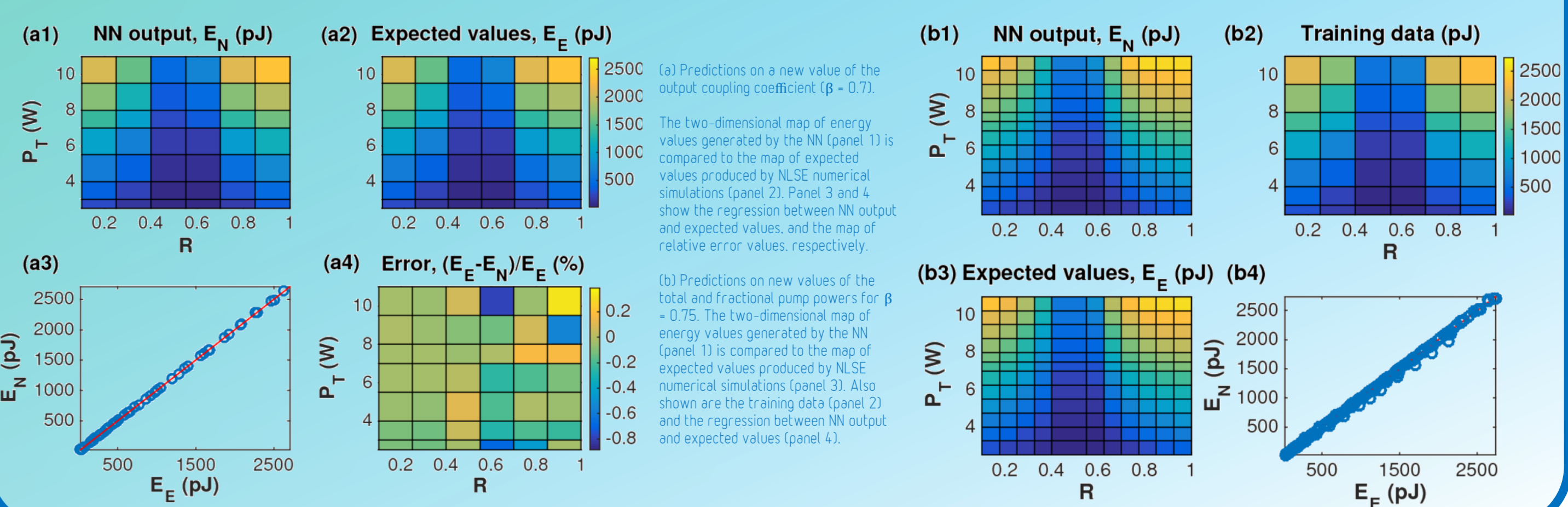
DIRECT NUMERICAL SIMULATIONS

➤ Adjustment of the cavity parameters provides access to a variety of pulse regimes that differ from each other not only quantitatively in terms of main pulse parameters, but also qualitatively.



NEURAL-NETWORK TRAINING

➤ A NN regression model provides a rapid and precise identification of the attainable output properties.



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