Automating physical intuition in nonlinear optics

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Machine learning has revolutionized nearly every aspect of photonics, introducing new methods for data analysis, and powerful algorithms for the active control and optimization of lasers. These experimental advances are remarkable, but machine learning can do far more, and can have just as much of a revolutionary impact on theory. For instance, algorithms can now autonomously discover new physical laws from data, and can enhance our understanding of the complex dynamics of nonlinear systems. In other words, the modeling of physical systems no longer relies solely on human insight and intuition; machine learning can drive entirely new directions in theoretical research.

An important initial advance in optics was the use of supervised clustering and regression to analyze instability dynamics in optical fiber [1]. Ultrashort pulse propagation in fiber is governed by the nonlinear Schrödinger equation and its extensions, involving various processes such as Kerr nonlinearity, dispersion of multiple orders, and inelastic Raman scattering. Understanding the interplay between these effects has always posed an enormous problem for researchers, and yet a clear physical interpretation of these interactions is vital for key applications such as pulse compression, frequency combs, and supercontinuum generation.

In our recent work [2], we have now developed a *fully unsupervised* machine learning technique that solves this problem algorithmically in a manner that does not require human interpretation. The method, adapted from concepts originally applied in ocean science, turbulence modelling and applied mathematics [3-5] can autonomously identify the dominant physics associated with specific regions of pulse propagation, revealing new insights into the physics of fiber soliton compression, optical shock formation, and soliton fission in supercontinuum generation.

The underlying idea of this *dominant balance* algorithm is to firstly compute the spatio-temporal evolution of pulse propagation by numerically integrating the governing differential equation. Subsequently, we calculate the relative magnitude of each term in the equation to determine how different combinations contribute to satisfy the equality where the sum of terms must equal zero. This powerful concept allows us to automatically detect regions of evolution where only a subset of terms possess significant magnitude, whilst all other terms are negligible. So that the procedure is performed without any human input, our implementation uses statistical Gaussian mixture model clustering followed by the application of a combinatorial metric as a threshold. This yields a robust and fully unsupervised method to determine how different regions of evolution are associated with different physical interactions. Our work is also the first application in any physical system to identify dominant balance regimes in both temporal and spectral domains.

This algorithmic approach to interpreting complex dynamics provides a fresh way for researchers to think about seemingly well-known phenomena, and opens up new windows into applying approximate theoretical methods since it can automatically detect limiting asymptotic regimes. Most importantly, the technique is general and not in any way limited to ultrafast fiber optics. Indeed, it can be readily extended to all systems where dynamics are described by differential equations, and there is tremendous promise to find wide application across photonics.

References

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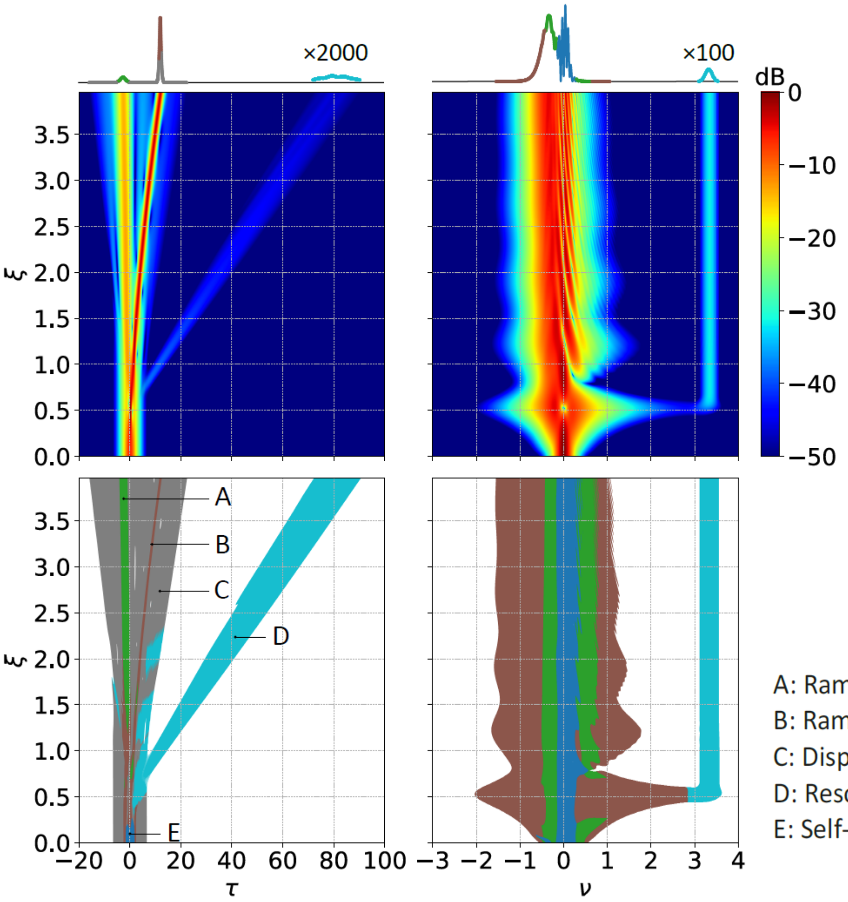

Generalized nonlinear Schrödinger equation

$$i\psi_\xi + \psi_{\tau\tau} + i\delta\psi_{\tau\tau\tau} + |\psi|^2\psi + \rho\psi\left(h_{\mathrm{R}} * |\psi|^2\right) = 0$$

Dominant balances

	$i\psi_\xi$	$\psi_{\tau\tau}$	$\psi\|\psi\|^2$	$\psi_{\tau\tau\tau}$	R
B	■	■	■	■	■
A	■	■	■		■
D	■	■		■	
E	■		■		
C	■	■			

A: Raman soliton
B: Raman soliton & third-order dispersion
C: Dispersive background
D: Resonant dispersive wave
E: Self-phase modulation

Figure: Automated interpretation of the physics of soliton fission in temporal (left) and spectral (right) domains for the generalized nonlinear Schrödinger equation as shown. The top images show the propagation evolution maps as well as output temporal and spectral profiles with the dispersive wave components (light blue) scaled as indicated. The bottom plots and accompanying color map show how the algorithm identifies different interaction regions allowing the automatic unsupervised association with physical effects as shown (A-E).