Analog Optical Computing

Bahram Jalali and Daniel Solli

UCLA Department of Electrical Engineering, Los Angeles, California, USA

Early attempts at optical computing did not lead to fruition because they aimed to create an optical equivalent of the digital computer. Despite significant investment and promise, the lack of an energy-efficient, compact optical switch and a practical form of optical memory have presented major barriers.

Although digital electronic computers have enjoyed exponential growth in capability as expressed by Moore's law, detailed numerical studies of complex systems is still often prohibitively time consuming. The problem is exacerbated in stochastically-driven nonlinear systems, which may support a vast number of possible states and trajectories.

This predicament has renewed interest in optical computing as an analog engine able to serve as a specialized processor to augment digital electronic computers. In ultrafast optical systems, dynamics occur much more rapidly than they can be simulated by a digital computer. Nonlinear optical systems can then be treated as compact proxies for much larger or less accessible dynamics governed by similar nonlinear interactions. An analog computer based on a nonlinear optical proxy system may have an advantage in computation time and energy dissipation over digital computers in the study of complex nonlinear dynamics involving, e.g., the propagation of water waves or optical pulses.

Optical fibers, semiconductor (e.g., silicon) waveguides, and dielectric (e.g., silicon nitride) waveguides offer rich nonlinear environments for realization of these analog optical computers. Mode-locked lasers and gain-switched lasers, which are able to generate pulses at high repetition rates, provide the means to probe numerous trajectories of a system in a short period: hundreds of millions or billions of trajectories resulting from a complex nonlinear interaction can be acquired in a 1-second interval using such sources. Such an experimental platform generates output 8-9 orders of magnitude more rapidly than they can be simulated with a digital computer.

The promise of these real-time computers is contingent on having an instrument with equally fast real-time acquisition speed. Conventional "ultrafast" measurements based on pump and probe (strobe light) methods cannot be used as they require repetitive excitation. Such techniques do not capture a fast event in real-time but rather reconstruct it from multiple measurements of identical occurrences. Photonic time stretch is currently the only method that allows real-time measurement of optical transients at megahertz repetition rates and beyond. The time-stretch implementation of a spectrometer, known as the time-stretch dispersive Fourier transform (TS-DFT), has been used to acquire $\sim 10^6$ consecutive spectra resulting from a complex nonlinear interaction in a brief interval and limited only by the memory depth of the digitizer. This technology has led to the discovery of counterintuitive phenomena such as optical rogue waves, and it has permitted observation of the birth of mode-locking, detection of structures in relativistic electron beams, and measurement of the dynamics of soliton molecules. Vast libraries of data can be collected in short intervals to reveal phase transitions, the onset of instabilities, and other rare phenomena. Time-stretch measurements enable nonlinear optical systems to serve as powerful platforms for investigating non-repetitive dynamics in hydrodynamics and other complex interactions.