Dual-comb technique as a tool for probing laser pulse generation dynamics (DuCT-LaserProbe)

Motivation. The discovery of solitary waves (solitons) in hydrodynamical systems by John Scott Rusell in 1834 has started a new chapter in the understanding of nonlinear wave propagation. Almost two centuries later, the self-reinforcing wave that maintains its shape while propagating at a constant velocity is no longer restricted to mechanical waves. Instead, it frames the core concept of optical pulse generation: solitons are a result of a balance between nonlinear and dispersive effects in the laser cavity that enables an optical pulse to travel long distances without changing its shape. Nowadays, soliton pulsed lasers find a wide range of applications across many disciplines like biomedical imaging, material processing, laser spectroscopy, and many others.

Although one would expect a clean single soliton pulse to emerge and propagate indefinitely in a laser cavity, tight optical confinement and pronounced optical nonlinearities often give rise to bound soliton states, i. e. when solitons split and group into pairs or multi-pulse groups often referred to as soliton molecules (SMs) due to the way such structures resemble chemical molecules. For laser engineers, this state is highly undesired because it lowers the laser peak power, affects the stability, and the feasibility of shifting its spectrum to a different wavelength. However, from a laser physics perspective, the rich nonlinear dynamics of solution molecule formation and mutual soliton interactions may help to understand complex nonlinear optics phenomena. Also, future optical memories or telecommunications systems may take advantage of multiple pulses per cavity roundtrip to code information. In this context, greatly desired are rapid laser pulse diagnostic techniques to characterize the formation, propagation, and stability of optical solitons at high frame rates and high temporal resolution at different wavelengths. The obtainable frame rate aims to fill the gap between pulse-by-pulse techniques like dispersive Fourier transform (DFT), and time-averaged like intensity autocorrelation or optical spectrum analysis.

Planned research. To address the demand from the two potential user groups: (1) laser engineers, and (2) physicists studying nonlinear optics phenomena, we envision the development of two soliton molecule imaging (diagnostic) techniques that employ a pair of pulsed lasers with detuned repetition rates. The concept builds on the idea of dual-comb spectroscopy, where two asynchronous pulse trains interact with each other on a photodetector. The first technique, known as the electric-field cross-correlation technique (EFXC) is planned to be generalized to enable studies between complex multi-pulse structures in novel dual-comb lasers that employ spatial multiplexing like microresonators or single-cavity dual-comb lasers. Such are receiving continual attention due to their potential for unstabilized optical frequency comb spectroscopy without moving parts for atmospheric sensing.

The other technique that measures the optical inter-pulse intensity cross-correlation (IXC) is tailored for rapid laser diagnostics and imaging SM beyond the conventional optical bandwidth limit of aliasing. Unlike conventional dual-comb detection, two photon-absorption in IXC allows the probing and imaged (diagnosed) laser to operate at completely different wavelengths. Phase-insensitivity lowers requirements on the frequency stability, which permits two unstabilized lasers to probe each other on a photodetector and observe a temporally-stretched intensity profile directly on an oscilloscope over a full cavity roundtrip. This lifts the constraints of conventional laser diagnostics relying on finite-range optical autocorrelators, coarse-resolution optical spectrum analyzers, and microwave spectrum analyzers. This ability has not been demonstrated to date.

Expected outcome. We anticipate the development of two real-time laser diagnostic techniques with different purposes, which will help us understand the complex soliton dynamics of lasers based on different mode-locking mechanisms. It should be possible by studying the pulse temporal profiles measured at kilohertz to sub-megahertz frame rates. We envision that two-photon detection in IXC will allow us to characterize lasers operating in more difficult spectral regions using mature telecom-grade sources. The EFXC technique, in turn, by means of multi-pulse generalization, should allow us to study complex SM-SM interactions that plague the spectral profiles of emerging comb sources for moving-parts-free optical spectroscopy.