Wavelength-Agile Dual-Comb Diagnostics of Pulsed Lasers

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Abstract: We show multi-kHz rate laser pulse diagnostics that rely on two-photon detection in a dual-comb configuration without mutual spectral overlap or polarization alignment between the sources. The technique enables us to probe soliton molecule dynamics. © 2022 The Authors

1. Introduction

Lasers emitting light in the form of pulses play a critical role in scenarios that require high peak optical powers delivered in short time intervals. While the most obvious application area is laser micromachining, the field of nonlinear optics also greatly benefits from pulsed emission [1]. This relates to the dependence of the frequency conversion efficiency on the peak optical power. Other important niches are biomedical imaging or multi-photon microscopy, which utilize longer-wavelength pulsed excitation to improve the sample penetration depth and lower photodamage effects [2].

Despite these advantages, the pulsed operation may trigger various nonlinear phenomena inside the laser cavity. This in turn affects the temporal intensity profile. Excessive levels of pump power often give rise to the emission of multiple bound optical pulses, which for soliton lasers is referred to as a soliton molecule. Such multi-pulse aggregates (with greatly reduced peak powers) often go unnoticed due to the speed and/or resolution limitations of conventional laser diagnostic techniques like an optical spectrum analyzer (OSA), radio-frequency (RF) spectrum analyzer, or intensity autocorrelator (IAC). A potential remedy to this issue is provided by two-photon dual-comb imaging of the laser intensity profile [3]. Nonlinear two-photon detection with a semiconductor photodiode [4] yields an intensity cross-correlation (IXC) signal between a pair of lasers with virtually no polarization or wavelength-match requirements. By employing the asynchronous pulse interaction of dual-comb spectroscopy (DCS) [5], an IXC signal is measured over a full cavity roundtrip time without any moving parts.

2. Results

The experimental setup of two-photon IXC diagnostics is shown in Fig. 1a. A pair of pulsed lasers with slightly detuned repetition rates Δf_r, referred to as a laser under test (LUT) and local oscillator (LO), is combined to interact on a photodiode (PD, here silicon) operating in a two-photon regime. Intensity-dependent, rather than interferometric detection lifts the requirement of mutual spectral overlap. A local maximum of the IXC signal is produced when optical pulses from the two sources temporally coincide (Fig. 1b). Instead of mechanically scanning the optical delay, discrete-time lag advances from pulse pair to pulse pair due to the repetition rate difference, as in DCS. In contrast, however, the aliasing limit that restricts the probed signal bandwidth in DCS is eased [3,4]. Multi-THz-spanning sources (60 nm at 1550 nm) with f_r=100 MHz rates can be readily diagnosed at rates violating the Nyquist criterion 120× times, albeit at the expense of IXC signal strength (Fig 1c). Lasers with milliwatt average powers and no mutual spectral overlap are fully compatible with this technique.

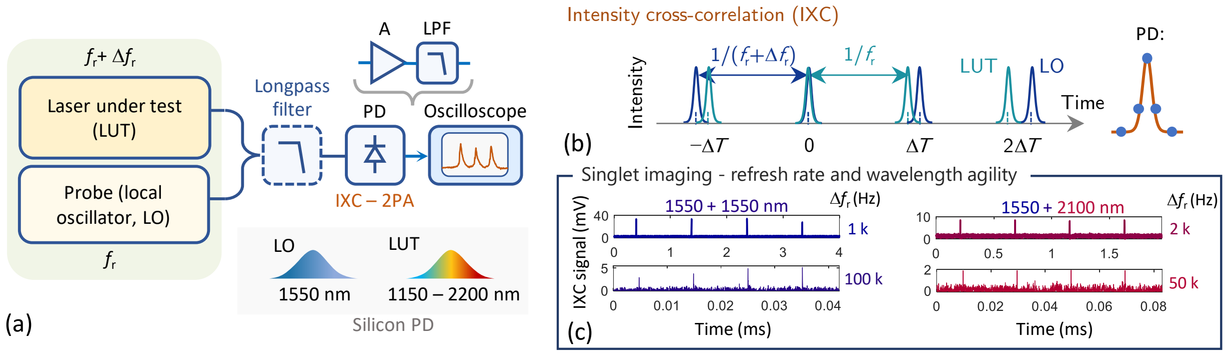

Fig. 1. Two-photon IXC diagnostics of pulsed lasers. (a) Experimental setup. PD – photodetector, A – pulse amplifier, LPF – low-pass filter. (b) Time-domain picture of pulse interaction in IXC. (c) Validation of the wavelength agility and violation of the Nyquist criterion of two-photon IXC diagnostics. Left: Both lasers operate with spectral overlap at ~1550 nm, Right: the LUT operates at 2100 nm with the LO at 1550 nm. An increase in the repetition rate difference above the aliasing limit lowers the IXC signal strength.

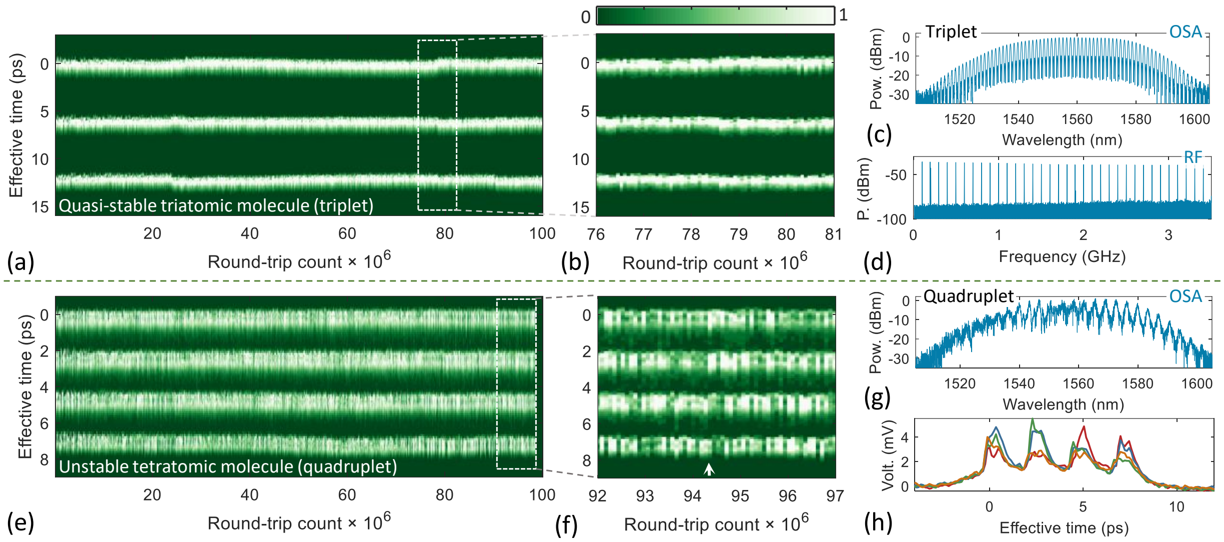

Fig. 2. Two-photon dual-comb diagnostics of a pulsed laser operating in a stable soliton triplet (a–d), and an unstable soliton quadrupled (e–h) state. The emission of multiple bound optical pulses via asynchronous interaction on a two-photon detector is possible at a multi-kHz rate while maintaining sub-ps temporal resolution. (a) Image of the soliton trajectory when three bound pulses exist in the cavity. (b) Zoom of (a). (c) OSA spectrum. (d) Radio frequency spectrum. (e) IXC image in the soliton quadruplet case. (f) Zoom of (e). (g) OSA spectrum. (h) Four consecutive frames from the image region marked by white arrow.

As expected for asynchronous interaction, the IXC signal is periodic with $1/\Delta f_r$. By applying a co-moving time frame [6,7], we produce an image of the optical pulse trajectory over a full cavity roundtrip time, here with a ~1.4 kHz frame rate. This enables us to study two distinct modes of operation of a soliton fiber laser with excessive optical pumping, as shown in Fig. 2. Figures 2a–d plot the diagnostics of an indefinitely stable soliton triplet – an aggregate of three tightly bound optical pulses separated by 6.2 ps, which yields a strongly modulated optical spectrum with ~161 GHz modulation period (2c). Note that the RF spectrum does not show any anomalies.

Further increasing the pump power switched the laser operation to an unstable soliton quadruplet state (Fig. 2e–h). Throughout the acquisition, the laser exhibited rich nonlinear dynamics. The pulses were constantly changing their intensities – rarely were all four pulses identical. Instead, behavior similar to mode competition in semiconductor lasers could be observed. This finds confirmation in the simultaneously measured OSA spectrum, which looks noisy and lacks the regular structure of Fig. 2c. This can be explained by studying four consecutive frames from the IXC image, as plotted in Fig. 2h. Two out of four pulses typically dominate.

3. Conclusion and outlook

We have demonstrated wavelength-agile pulsed laser diagnostics that employ two-photon detection in a dual-comb configuration. A 1550 nm laser acting as a local oscillator has been successfully used to diagnose the temporal intensity profile of a repetition-rate-mismatched laser under test with ~2100 nm center wavelength even at frame rates far above the Nyquist limit (80×). We have also imaged the rich dynamics of soliton molecules in a fiber laser with kHz rates. The exploitation of two-photon detectors with lower bandgap energies like InGaAs will grant us access to studies on emerging pulsed lasers at wavelengths extending to the mid-infrared region, which are difficult or impractical to diagnose using conventional pulse characterization techniques. We will additionally discuss the feasibility of probing even more exotic laser states like a soliton rain [3].

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