EPJ Web of Conferences **307**, 02026 (2024) https://doi.org/10.1051/epjconf/202430702026
EUROPHOTON 2024

A synthetic pulse interaction for modelocking at ~100 GHz

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Abstract. Harmonic modelocking allows high repetition rates but has limited controllability and scalability. We propose a synthetic pulse-to-pulse interaction, acting like a saturable absorber, but imparting loss as a function of temporal delay, as a route to ultrahigh frequency fiber lasers.

Diverse applications, from efficient material processing [1] to frequency combs [2], would benefit from high repetition rate ultrafast laser pulses in the range of 10s, even 100s of GHz. While there has been commendable progress in fundamental mode-locking [3], physical dimensional requirements severely limit the repetition rates and microresonator-based sources are limited to low powers. Harmonic modelocking of fiber lasers offers a power-scalable alternative, but robust, repeatable, and low-noise harmonic operation has proven elusive. Recently, we clarified the physical reasons for these persistent difficulties through a formal analogy between harmonical pulses and trapped Brownian particles, and reported robust and low-noise operation [4], albeit at low repetition rates. To reach much higher repetition rates, at least two additional advances are necessary. The first is a clear recipe for the creation and annihilation of pulses so that any desired harmonic number of pulses can reliably be assembled starting from a single pulse, i.e., the onset of fundamental modelocking. We demonstrated promising results up to the 110th harmonic [5], but its repetition rate was still limited by the underlying acoustic pulse-to-pulse interactions. The second requirement is a strong interaction mechanism that works for pulse-to-pulse temporal separations as short as several picoseconds and prohibits anharmonic pulse patterns.

Here, we propose and experimentally demonstrate, albeit currently outside a cavity, a synthetic nonlinear interaction mechanism that imparts a loss that takes a minimum value for a certain (externally adjustable) temporal separation between consecutive pulses. This mechanism, which we call a nonlinear time filter, plays a role similar to a saturable absorber, except that the loss is a function of temporal separation rather than intensity. Thus, combined with the laser gain, the nonlinear time filter results in a higher-gain window trailing each pulse (Fig. 1a). As we show through numerical experiments, in a cavity with a nonlinear filter, when a new pulse is created, it positions itself behind the existing pulse to minimize its loss at the nonlinear time filter. This new pulse similarly creates an unoccupied gain slot. If another pulse is created (or injected externally and supported) by increasing the pump power, the new pulse similarly positions itself at this gain slot. Thus, the number of pulses can be grown one pulse at a time until they populate the entire (ring) cavity and the last pulse links up with the first one.

In our preliminary experiments, the nonlinear time filter is implemented by inserting a spectral filter with a double passband into the cavity as shown in Fig. 1b. After passing through this filter, two smaller pulses (a blue-shifted and a red-shifted pulse) are obtained. Their frequency difference is adjusted to near the peak of the Raman gain. The blue-shifted pulse acts as our “mediator” (in loose analogy to particle-particle interactions conveyed by mediators in particle physics), while the red-shifted pulse is the main one that will circulate the cavity. The mediator is retarded by a delay arm to the vicinity of the red-shifted of the trailing pulse. The mediator creates a Raman gain, thus transferring energy to the trailing main pulse. This energy transfer is maximized when they overlap optimally. The double-band spectral filter can be natively incorporated into a Mamyshev oscillator (under construction) [6]. We present experimental proof of concept of the nonlinear time filter (Fig. 1c). By sending a pair of pulses with a varying delay to the double passband filter, we measured the transmitted power in a setup that corresponds to the open loop version of the one depicted in Fig. 1b.

A realistic simulation of this oscillator design shows that it takes as little as tens of roundtrips to organize the pulses into an equidistant pattern. This rapid evolution corresponds to pulse interactions that are orders of magnitude stronger than the interactions underlying passive harmonic modelocking [4] and is much closer to the evolution rate of individual modelocked pulses under the influence of, e.g., a saturable absorber. Furthermore, once the pulses are mutually locked to a fixed temporal spacing, the resulting pulse train behaves like a single highly energetic waveform consisting of regularly spaced peaks because the overlap of the mediator and main pulses couples their mutual phases through cross-phase modulation. As a result, the simulations indicate the locking of the mutual phases of the pulses in addition to their temporal spacings. This has important implications, firstly, a much stronger suppression of the supermodes [7] and, possibly, a far lower quantum noise limit [8]. The underlying dynamics and these features qualitatively distinguish the resulting laser state from regular harmonic modelocking, suggesting it constitutes a new regime, where the pulses experience a second level of self-organization, i.e., mutual locking of their temporal spacings and, likely, phases, akin to how the cavity modes lock up in fundamental modelocking. Having recently moved from our former institution to the current one, we are currently working to recreate the experimental setup to implement the nonlinear time filter inside a Mamyshev oscillator.

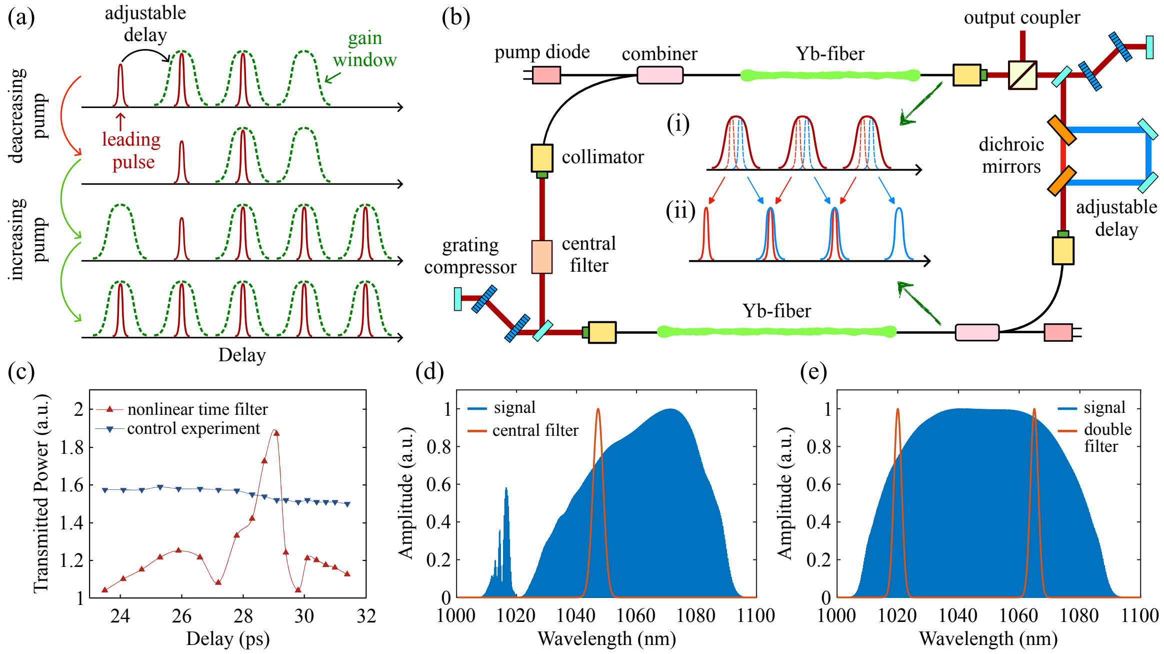

Figure 1: The nonlinear time filter concept and its implementation. (a) Each pulse generates a high gain window at an adjustable delay. Decreasing the pump power kills the leading pulse, and increasing it generates pulses through the empty gain window at the rear, ultimately filling the cavity. (b) A schematic of the preliminary setup based on a modified Mamyshev oscillator with a double-passband spectral filter, extracting blue and red sub-components of each pulse (i). The adjustable delay retards the blue sub-component to interact with the following red sub-component (ii), resulting in a Raman gain. (c) An experimental confirmation of the temporally dependent gain. The delay axis refers to a pair of pulses, which we injected externally to point (i) in (b). The power axis refers to a measurement after the central filter. The control experiment refers to blocking the beam in the delay arm, which carries the blue sub-component. The remaining part of the laser is under development. (d, e) the spectra falling at the central and double filters (simulation).

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