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Hierarchical slaving for superior harmonic modelocking

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Despite its significance, control of multi-pulsing in modelocked lasers has had minimal success. We propose a conceptually new approach that self-organizes multiple pulses inside the cavity through a novel multi-scale interaction. The pulses in our laser are nonlinearly coupled through an acoustic effect but additionally through their nonlinear losses and the gain dynamics, resulting in a hierarchical interaction manifesting at the individual pulse level and collectively. We present an analytical model that conceptually extends the "slaving principle" of H. Haken for complicated dynamical systems to a hierarchical implementation over multiple levels, each distinguished by its timescale. While multi-timescale interactions are not new to modelocking, the hierarchical slaving perspective clarifies how to exploit such interactions for controlled evolution of the pulse pattern leading to harmonic modelocking (HML). In practice, we obtained reliable and stable HML with $\gtrsim 50$ dB supermode suppression (SS) in a Mamyshev oscillator with variable filter offsets and *asymmetric* amplification arms (fig.1a). The pulse propagation is dominated by Kerr nonlinearity in one arm and similariton propagation in the other. All fibers are polarization-maintaining for environmental stability. Through the filter settings, we tune the pulse energy, which, equivalently, determines the number of pulses. The acoustic effect couples the energies and, consequently, the speeds to the temporal positions of the pulses, and this coupling allows us to control the pulse interactions by fine-tuning the filter settings. We achieved HML at every harmonic of our laser up to 1.2 GHz (83rd harmonic), limited by the average power (Fig.1). The output pulse duration was 150 fs, and the energy was 2 nJ at 1.2 GHz. To our knowledge, no fiber oscillator combines such a high repetition rate, strong SS, and short pulse duration [1, 2]. Moreover, these HML states are indefinitely stable. The slaving principle results in a simple dynamical model involving a 1D iterative map that describes the energy of each pulse [3]. By successively invoking the slaving principle to processes of higher timescales, we reach a differential system that describes the pulse positions, taking into account the acoustic effect and its coupling to the energies and speeds of the pulses. This model relates the nonlinear loss at the filters to the overall laser dynamics (fig.2) and clarifies how the pulse interactions can be controlled through the filter settings.

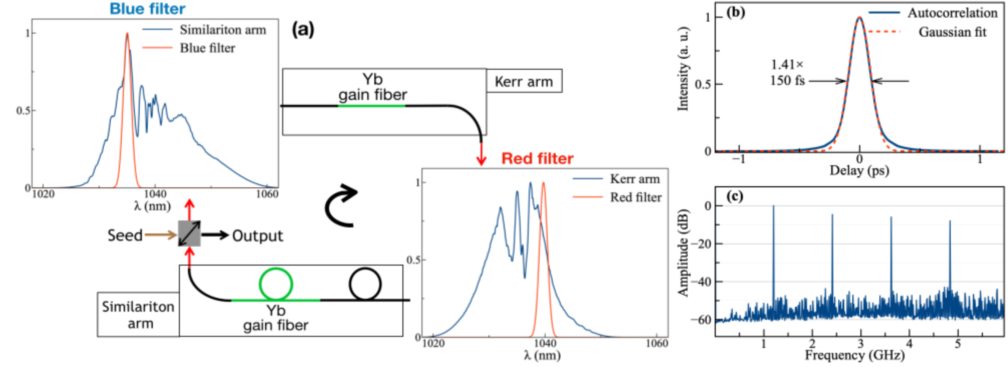

Fig. 1 (a) Schematic representation of our laser, showing the filters and the incident spectra for the 1.2 GHz state. (b) Autocorrelation of dechirped output pulses (similariton arm). (c) Radio Frequency spectrum showing ~50 dB SS

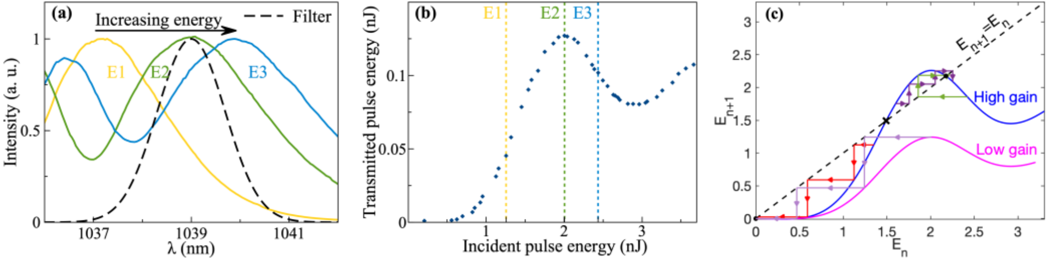

Fig. 2 (a) The red-most lobe of the Kerr arm spectrum at 3 different pulse energies and the subsequent filter. (b) The nonlinear transmisssion curve arising from the displacemmet of the spectral lobe. (c) Trajectories on typical energy maps. *n* denotes the roundtrip. The cross and dots indicate unstable and stable fixed points, respectively.

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