Real-Time Transition Dynamics of Harmonically Mode-Locked Femtosecond Ultralong Ring Fiber Lasers

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Abstract *The transition dynamics between harmonic mode-locking states in Raman-assisted ultralong ring fiber lasers assisted are experimentally studied. The results confirm the expected solitonic behaviour associated to the quasi-lossless extended cavity, but also showcase unusual intermediate states that could inform system design for tunable operation.*

Introduction

Mode-locked fiber oscillators stand out as simple and inexpensive solutions among the available technologies for ultrashort pulse generation, albeit traditionally limited in terms of power and thus restricted in their fields of exploitation unless paired with additional amplification and compression stages. Our recent demonstration of ultralong Raman-assisted femtosecond mode-locked ring fiber lasers cleared up a path for the overcoming of this limitation using reduced cost components and conventional communications fiber [1,2].

These lasers, reliant on the use of InN-based semiconductor saturable absorber mirrors (SESAMs), operate at a central wavelength of about 1560 nm, and offer stable operation with pulse widths of the order of 200 fs and repetition rates below 100 kHz, through careful management of the loss and dispersion dynamics, with the use of distributed Raman amplification, to guarantee adiabatic soliton transmission in the extended multi-km cavity, that can reach tens of km [3]. The characteristics of this new family of lasers makes them ideal candidates for applications such as supercontinuum generation and environmental monitoring [2], industrial marking and material processing, but there is still much to explore regarding their flexibility and potential limitations.

In this new work we make use of the time-stretched dispersive Fourier transform technique [4] (TS-DFT) to explore, in real time, pulse formation and the transition between harmonic mode-locking states for different ring lengths and amplification setups, shedding light on system dynamics and offering insight into the optimal transition paths for mode tunability.

Experimental set-up

Our laser setup, represented in figure 1, is largely polarization-insensitive thanks to the polarization independent response of the InN SESAM, which is also resistant to high irradiances [5]. Average output power is dictated by an Erbium Doped Fiber Amplifier with nonadjustable gain, operating at a fixed 24 dBm maximum output saturated power at 1560 nm. For the purpose of our current study, the extended cavity can comprise either a 2.4 km or a 5.4 km spool of ITU G.652 standard single-mode fiber (SSMF), inserted right after the SESAM. Losses at the

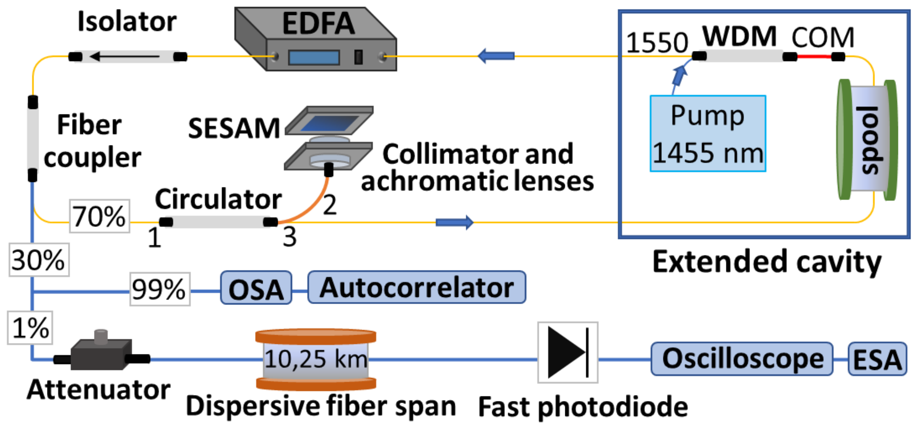

Fig. 1: Schematic of the setup for the characterization of ultralong pulsed fiber lasers, where the extended cavity can take different lengths.

SESAM, that operates in free space, are controlled through focus and spot size, and adjusted to guarantee propagation under adiabatic soliton conditions in the amplified extended cavity, opening up the possibility of achieving mode-locking inside the ultralong ring laser [6] while maintaining pulse duration in the range of the hundreds of femtoseconds. The reduced attenuation of the pulse in its propagation through the extended fiber spool is guaranteed in the long cavity by partially or totally compensating fiber loss using distributed Raman amplification [7] with a backward propagating 1455 nm semiconductor laser diode capable of providing up to 700 mW.

Laser output is characterised by simultaneously monitoring it through an autocorrelator, an optical spectrum analyser and the aforementioned TS-DFT setup, in which the signal is attenuated 45 dB to achieve linear transmission through a 10.25 km standard single mode fiber dispersive span and then directed to a fast photodiode, monitored through an electrical spectrum analyzer and recorded in a real-time oscilloscope capable of capturing 10 GSamples/s with a 10-bit resolution depth.

Results and discussion

As an example of our full characterisation, figure 2 illustrates the real-time transition dynamics between the fundamental mode and the 2nd harmonic in an ultralong 5.4 km ring in which Raman pump power has been adjusted to fully compensate for the losses in the extended cavity section. Mode transition is forced by adjusting focus in the SESAM, going from a noisy fundamental mode with a noticeable ASE peak around 1530 nm (see initial optical spectrum on the bottom row) to a much cleaner second harmonic. Interestingly, the transient state involves the generation of two soliton-like pulses at 1/4 and 3/4 of the time period, which behave as adjacent in-phase solitons, attracting each other and eventually merging at the exact half period position after a few tens of cycles.

Although the solitonic dynamics of the generated pulses are consistent with the propagation powers and quasi-lossless conditions in the extended cavity, the fact that the transition from the fundamental mode to the 2nd harmonic is mediated by what seems to be an unstable, transient 3rd harmonic seems both unusual and rather characteristic of our particular system. Moreover, this behaviour is highly repeatable, and present in all our experimental observations of this transition, both for the 2.4 km and the 5.4 km rings.

The direct transition from the fundamental mode to the 3rd harmonic (see figure 3, corresponding to the 2.4 km cavity case) is similarly unique. From the fundamental mode the system goes into a transient state in which two pairs of in-phase soliton like pulses appear, which merge after a few cycles at precisely 1/4 and 3/4 of the initial period, and finally stabilize into a train of identical pulses. As in the previously discussed transition illustrated in figure 2, this behaviour is highly repeatable and the only observed transition from the fundamental to the 3rd harmonic.

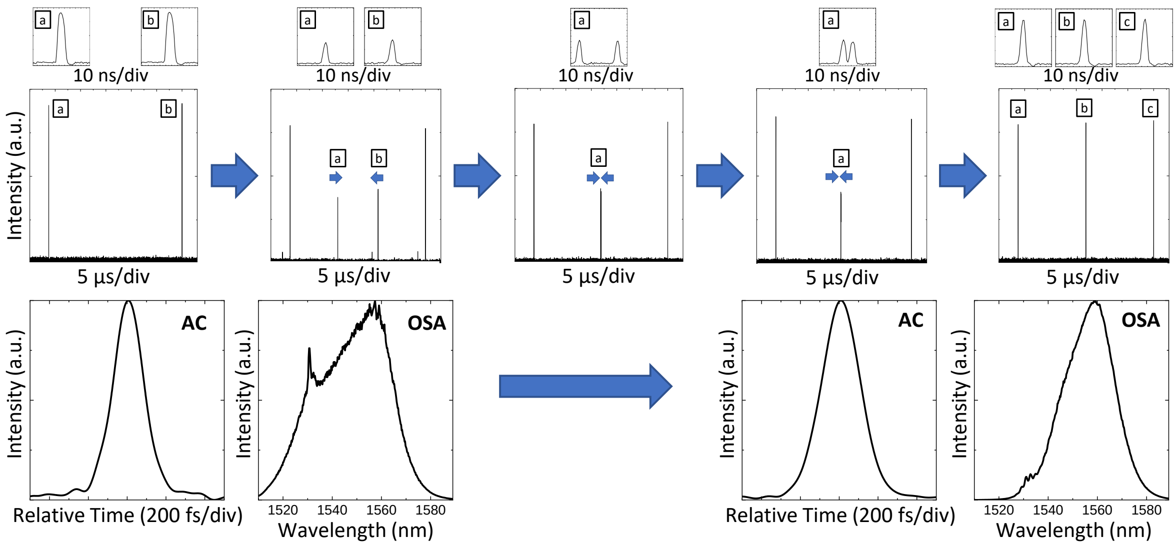

Fig. 2: Transition from fundamental to 2nd harmonic mode-locking in the amplified 5.4 km ultralong laser. **Top** - Pulse sequence evolution. Showing initially the fundamental mode, then the apparition of two in-phase soliton-like pulses appearing at 1/4 and 3/4 of the time period, that attract each other until they merge exactly at 1/2 period, point at which the laser stabilizes in the 2nd harmonic. **Bottom** - Autocorrelation and optical spectrum traces in the fundamental (left) and 2nd harmonic modes (right).

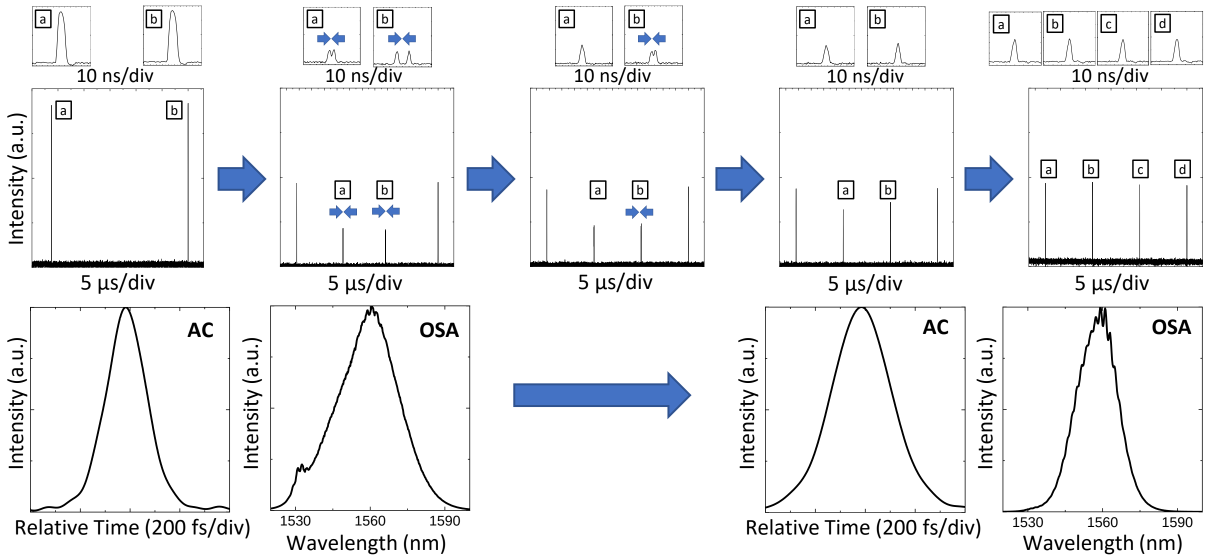

Fig. 3: Transition from fundamental to 3rd harmonic mode-locking in the 2.4 km ultralong laser. **Top** - Pulse sequence evolution. Showing initially the fundamental mode, then the apparition of two pairs of in-phase soliton-like pulses appearing in the vicinities of 1/4 and 3/4 of the time period, that attract each other until they merge at the aforementioned points. **Bottom** - Autocorrelation and optical spectrum traces in the fundamental (left) and 3rd harmonic modes (right).

Furthermore, for all lengths and amplification configurations studied, there seem to be multiple forbidden direct transitions. For example, no direct path for the transition between the 2nd and 3rd harmonic has been experimentally found, the latter being achievable only through previous stabilization to the fundamental mode. This behaviour has direct implications in terms of system design for those applications in which a dynamic tunability of the repetition frequency could be desirable, such as material processing or broadband frequency comb generation, since the transition to higher frequency, lower energy pulses would have to be necessarily mediated by a temporary state with higher energy per pulse, which would have to be conveniently taken into account.

Conclusion

The real-time study of mode transitions in femtosecond ultralong ring fiber lasers offers relevant insight into their underlying solitonic dynamics and information on their potential for frequency repetition tunability.

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