

Recent progress in femtosecond pulsed ultralong fiber ring laser sources

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ABSTRACT

Ultrafast-ultralong ring fiber lasers represent a new passively mode-locked laser architecture reliant on the use of Raman-assisted nonlinearity management over cavities extending tens of kilometers and fast, polarization-insensitive saturable absorption. These new sources are capable of supporting the generation of stable pulses shorter than 200 fs with ultra-low repetition rates of a few tens of kHz, overcoming previous limitations to pulse duration and peak power imposed by dispersive effects. The unique characteristics of this new family of ultrafast fiber oscillators makes them suitable for a broad range of applications. In this invited talk we will review some of the latest advances on the topic, focusing on the optimal design and implementation of such lasers.

Keywords: Ultrashort pulse generation, mode-locked fiber oscillators, ultralong-ultrafast ring fiber lasers (UUFL), solitons, Raman amplification

1. INTRODUCTION

Ultrashort pulse generation in passive mode-locked fiber ring resonators has attracted great attention since the early 1990s [1, 2]. The use of a ring configuration and a saturable absorber [3] in the cavity facilitates self-starting mode locking and can result in the generation of very short pulses. Fiber lasers exhibit desirable characteristics such as stability, efficiency, compactness, easy integrability, and convenient output beam handling, which make them highly attractive. However, the direct applicability of these ultrafast fiber sources without the addition of external amplification stages reliant on techniques such as chirped pulse amplification [4] is still restricted in certain areas due to limitations in achievable pulse energy and peak power.

To overcome these limitations, a new family of passively mode-locked femtosecond pulse fiber oscillators has been recently developed. This family of ultralong ultrafast fiber lasers (UUFLs) relies on dispersion and nonlinearity management and uses polarization-insensitive InN-based semiconductor saturable absorber mirrors (SESAMs) in a multi-kilometer standard fiber ring with Erbium Doped Fiber Amplifier (EDFA)-based amplification [5]. These UUFLs have been shown to present inherently low repetition rates and produce low-chirp, high-power pulses centered at 1560 nm in the range of hundreds of femtoseconds, all without the need for neither pulse picking nor chirped-pulse amplification or any kind of external stages, reducing both cost and complexity in comparison to similarly capable sources. Moreover, support for ultrashort pulse generation over cavity lengths of up to tens of kilometers, with output pulse energies of the order of μJ , have been recently demonstrated with the aid of in-line distributed Raman amplification [6]. Moreover, the real time monitoring of the laser output through the time-stretch dispersive Fourier transform reveals the rich dynamics of these sources new family of lasers, which can operate in different, tunable harmonic regimes and power ranges [7].

One critical aspect of UUFL design is the precise management of power and nonlinearities inside the extended cavity to achieve stable mode-locking at femtosecond regimes. This is achieved by carefully adjusting signal power after the SESAM, so that pulse peak power at the input of the extended section of standard single-mode fiber (SSMF) is always close to that of a fundamental soliton. This allows for stable ultrashort pulse propagation as long as local intensity oscillations are low, so that pulses adapt adiabatically. In order to extend the cavity length while ensuring stable mode-locking with ultrashort pulse generation, the conditions for fundamental soliton propagation must be guaranteed. In longer rings, this can be achieved through virtually lossless distributed Raman amplification using, for example, cavity ultra-long Raman fiber lasers (URFLs) [8, 9], which support adiabatic, close-to-ideal soliton transmission over many soliton periods through SSMF. In other words, the introduction of an independently amplified section of fiber operating

in conditions close to transparency, similar to the approach proposed for the design of adiabatic soliton lasers [10], combined with an adequate in-line management of signal power, can be used to extend ring length while preserving ultrashort pulse support, with the corresponding reduction in repetition rate, and simultaneous increase in pulse energy and peak power.

2. EXPERIMENTAL SETUP

A typical ring fibre laser setup and its surrounding characterization scheme is represented in Fig. 1. Our basic system, presented in [5] includes an EDFA with a non-adjustable gain level operating at a fixed 24 dBm maximum output saturated power at 1560 nm. An InN SESAM, in free space configuration and coupled to the system through a circulator, is used to induce passive mode-locking. This SESAM is resistant to high irradiances and polarization independent and in our scheme leads to the generation of pulses with durations of the order of 100s of femtoseconds. The more advanced setup included here, which was presented in [6], adds two different amplifier configurations to pump the extended cavity

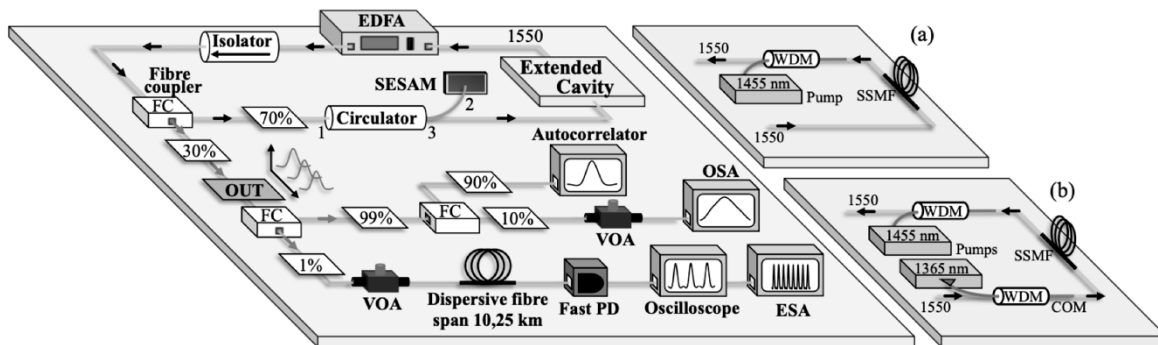


Figure 1. Schematic of the setup for the characterization of ultralong pulsed fibre lasers, where the extended cavity can take two different configurations, depending on the selected distributed amplification solution. (a) Single-wavelength backward Raman pumping and (b) Bi-directional second-order Raman pumping. The operation of the laser is counter-clockwise.

In order to characterize the system, the output pulses obtained at 1.56 μm are analyzed simultaneously in the optical domain through a power meter, a fast autocorrelator and an optical spectrum analyzer through the 30% port (the 70% - 30% values of fibre coupling provide the highest output power under mode-locking conditions). The signal is also characterized using the time-stretched dispersive Fourier Transform technique, TS-DFT, that allows us to observe the dispersively stretched pulses in real time in a fast oscilloscope after conversion to the electrical domain in a low-noise fast 25 GHz photodetector. The electrical signal is also routed to a radiofrequency spectrum analyzer for fast and precise monitoring of repetition rates and mode structure.

3. SAMPLE RESULTS

Fig. 2 displays sample results obtained for the 10 km extended ring, mode-locked to the 1st harmonic. Here we observe that overamplification leads to slightly shorter pulses at the expense of additional noise and reduced stability. The real-time profile of each broadened pulse in the oscilloscope qualitatively reflects the optical spectrum of the laser, minus a noise component centered at 1530 nm representing less than 6% of the total energy contained in the laser spectrum for the optimally amplified case. The estimated best output pulse energy from signal average power is of the order 1.05 μJ . Similar results are obtained for extended lengths of up to 25 km, with mode-locking to higher-order harmonics.

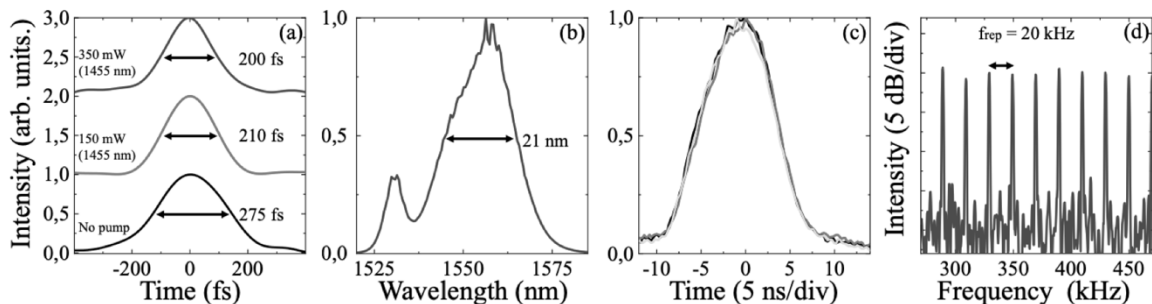


Figure 2. (a) Traces for the output pulsed signal in three amplifier configurations for the 10 km laser, including underamplified configuration (bottom), quasi-lossless (middle) and slightly overamplified transmission (top), with stable mode-locking to the 1st harmonic (repetition rate 20 kHz). (a) Autocorrelation traces. (b) Optical spectrum for the optimally amplified case. (c) Individual broadened pulse traces overlay after the TS-DFT section for the optimally amplified case. (d) RF spectrum.

Over the course of the presentation we will explore the regimes of operation under different cavity lengths and amplifier configurations, as well as their system stability, the transition dynamics between different harmonic modes and different potential routes for the optimization of laser output.

4. CONCLUSION

UUFs are compact fs sources displaying unique properties, including extremely low native repetition rates and high energies per pulse, all without the need for external amplification and compression. These unique characteristics and their reliance on relative low cost telecommunications-grade components make them an exciting development in the world of fiber lasers, and excellent potential candidates in applications such as supercontinuum generation, environmental monitoring [11], industrial marking, material processing or eye-safe LIDAR, to name a few.

ACKNOWLEDGEMENTS

This work was funded by Ministerio de Ciencia, Innovación y Universidades (grants RTI2018-097957-B-C33 - ECOSYSTEM and PID2021-128000OB-C21 - PRECISION), Comunidad de Madrid – Fondos FEDER (S2018/NMT-4326, SINFOTON2-CM) and Academy of Finland Flagship PREIN 320165. The authors wish to thank Prof. E. Monroy for providing the InN samples employed in the SESAM and Profs. F. B. Naranjo, M. González-Herráez and J.M. Soto-Crespo for their useful comments.

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