Mode-locked all-fiber laser with cascaded generation of Raman dissipative solitons

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***Abstract*—We demonstrate cascaded generation of first- and second-order Raman dissipative solitons in an all-fiber laser cavity. Optimization and coherent combining of dissipative soliton and second-order Raman dissipative soliton is performed.**

I. Introduction

Dissipative soliton (DS) regime is one of the most effective ways to generate energy-scalable femtosecond in mode-locked lasers [1], [2]. Energy scaling can be achieved by cavity lengthening when duration of highly chirped pulse increases at fixed peak power. However, the energy of chirped DSs generated in a long fiber laser is limited by SRS threshold. We have found that this effect can be used for generation of coherent highly-chirped Raman pulses at Stokes wavelengths named as Raman dissipative solitons (RDS) [3]. The formation of RDSs is possible with intracavity feedback provided by re-injection of the Raman pulse into the laser cavity with proper timing. Together, DS and RDS form a 2-color coherent soliton complex.

In this work we report on the first experimental demonstration of the cascaded generation of the 1st- and 2nd-order RDSs in the scheme with synchronous pumping in the common cavity of Yb-doped fiber laser [3], [4]. The regime was achieved by a similar way as the first-order RDS by adding a second loop of intra-cavity feedback.

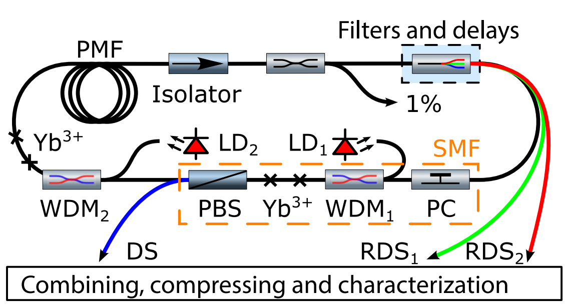


Fig. 1. The experimental setup.

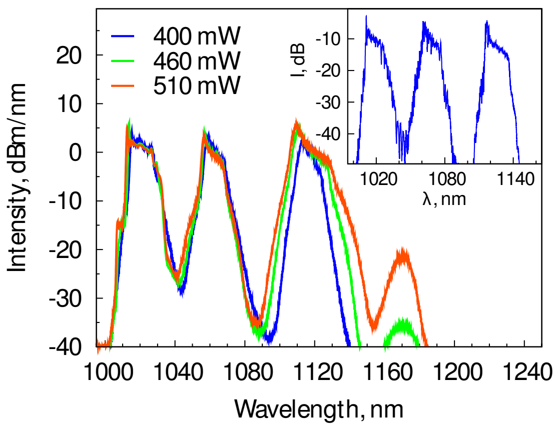
II. Results and discussion

The possibility of cascaded generation of Raman dissipative solitons was first demonstrated numerically in [3]. The following experimental realization is based on the results of the numerical predictions. In the early numerical prediction "hard" filters with stepwise transmission spectra were used for intracavity spectral filtering of the generated pulses. These filters eliminate the remaining small-amplitude parts of the Raman pulses and enable stable generation of RDSs. In this work numerical modeling was performed with "soft" filters that have sinusoidal transmission functions. In contrast to "hard" filters, "soft" filters can be easily realized in the experiment.

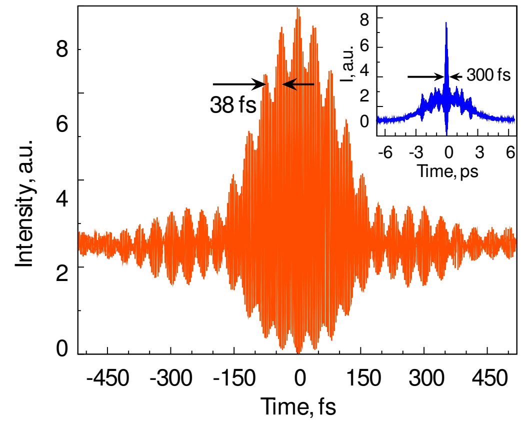
The experimental setup is shown in Figure 1. It includes a hybrid ring laser cavity comprising a short SMF part ($\sim$ 2 m for NPE mode-locking) and a long PM fiber part ($\sim$ 40 m for generating highly chirped DSs). The couplers, PBSs, WDM2, second piece of Yb-doped active fiber and isolator are made of a PM fiber. Such a configuration provides an effective pulse energy scaling via cavity lengthening [4]. Here we add a second pump laser diode (LD2) and a piece of active Yb-doped fiber to increase intracavity energy of a soliton complex. The total optical pump power reaches 650 mW at 976 nm. Laser operates at 4.3 MHz repetition frequency, that corresponds to cavity length $\sim$ 47 m. The difference in the group velocities of DS and RDSs is compensated by the bypass fibers of the feedback loops providing a necessary delays for the Raman pulses. Delay lines and Raman feedback were implemented with an array of all-fiber polarization-based Lyot filters with sinusoidal transmission functions. The length of all fiber tails was matched to ensure the correct delays between the pulses.

Dechirping of the pulses was performed by a classical diffraction gratings compressor. In case of coherent combining the compressor length was optimized for minimum DS duration. The spectra were measured by Yokogawa 6370 optical spectrum analyzer, the temporal characteristics of the output pulses by interferometric autocorrelator and by frequency-resolved optical gating system.

It turned out that all the pulses (DS, 1st- and 2nd-order



(a)



(b)

Fig. 2. (a) Experimental spectrum of three-color bound solitons at different pumping: DS(1020 nm), 1st-order RDS (1065 nm) and 2nd-order RDS (1120 nm) in experiment and simulation (inset); (b) Interferometric traces of the combined pulse (DS and 2nd-order RDS).

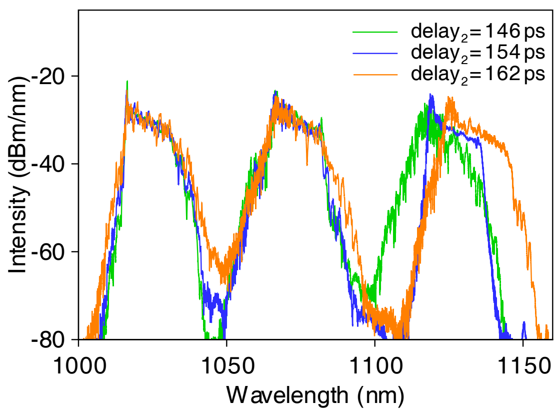


Fig. 3. Variation of the signal spectrum with the delay time for the 2nd-order RDS (delay_2) in simulation. Delay_1 = 87 ps. The Raman feedbacks for the 1st-order RDS and the 2nd-order RDS are: $R_1 = 10^{-6}$, $R_2 = 10^{-5}$.

RDS) are coherent, linearly chirped (chirp parameter is $>$100) and can be externally compressed to 200-300 fs duration in correspondence with their spectral widths of 10-20 nm centered at wavelengths 1020, 1060 and 1115 nm correspondingly, see Figure 2a. A coherent combining of each Raman component appears feasible, thus confirming coherence of the obtained 3-color soliton complex. Figure 2b shows the experimental results of coherent combining of DS and second-order RDS. The cross-correlation shows deep modulation demonstrating high mutual coherence of the solitons. The interval between fringes equals to 38 fs in corresponding to the frequency spacing between DS and 2nd-order RDS. At the same time, the width of the individual fringe of the trace is smaller than that of the single soliton, being defined by the whole spectral range of the solitonic complex.

The obtained experimental results have been compared with numerical simulation. Figure 2a shows the intracavity spectra of multisoliton complex both in experiment and simulation. The optical spectra of DS, 1st- and 2nd-order RDS have steep edges characteristic to a highly-chirped DSs. It could be also seen in the figure that pump power increase leads to generation of the 3rd-order noisy Raman pulse with wavelength 1160 nm, giving way to further increase of the bandwidth and energy of multi-color soliton complex. Note, that 2nd-order RDS is very sensitive to the Raman feedback loop parameters. We numerically optimized a scheme with two feedback loops, with the corresponding results shown in Figure 3. By numerically varying the delay time for the 2nd-order RDS, we found the optimum delay time that is about delay_2 = 154 ps (delay time for the 1st-order RDS was fixed: delay_1 = 87 ps). As one can see in Figure 3, a shift of only 8 ps leads to a significant change in the 2nd-order RDS spectral shape ans wavelength. Because the DS, 1st- and 2nd-order RDSs have different group velocities due to dispersion, delay times should be optimized independently.

III. Conclusion

We developed all-fiber laser scheme that offers efficient cascaded generation of Raman dissipative solitons. The generated pulses (conventional dissipative soliton at 1020 nm, 1st and 2nd order RDSs at 1065 nm at 1115 nm, correspondingly) are shown to be linearly-chirped and compressible to 200-300 fs. Moreover, they appear to be mutually coherent that has been confirmed by efficient coherent combining exhibiting $<$40 fs interference fringes within the combined pulse envelope. Besides development of femtosecond lasers at new wavelengths, other applications can benefit from realization of this approach, including frequency comb spectroscopy, transmission lines, seeding parametric amplifiers and enhancement cavities, multi-photon fluorescence/CARS microscopy etc.

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