Feedback-controlled Raman dissipative solitons in a fiber laser

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Abstract: Energy of chirped dissipative solitons (DS) generated in fiber lasers may exceed a threshold of stimulated Raman scattering (SRS) leading to formation of a noisy Raman pulse (RP). As we demonstrated recently, a feedback loop providing re-injection of the Raman pulse into the laser cavity can form a Raman dissipative soliton (RDS) with similar characteristics to those of the main dissipative soliton. Here, we present the results of feedback optimization of the generated RDS spectra. First experimental results of coherent combining of DS and RDS are also shown.

OCIS codes: (060.5530) Pulse propagation and temporal solitons; (060.2320) Fiber optics amplifiers and oscillators; (140.3550) Lasers, Raman; (320.7090) Ultrafast lasers; (190.5650) Raman effect.

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1. Introduction

The regime of dissipative solitons (DS) is a powerful technique for generating high-energy femtosecond pulses in mode-locked lasers based on fiber or other solid-state media [1, 2]. Stable DS pulses are formed inside the laser cavity due to a balanced action of nonlinearity and dispersion, gain and loss. Being intrinsically one-dimensional, stable and hands-free, all-fiber design of femtosecond oscillators is one of the most attractive technologies being intensively developed recently. In normal dispersion fiber cavities [2, 3], the energy of DS pulses is sufficiently higher than in the anomalous one due to the intra-cavity pulse stretching proportional to the cavity length. On the other hand, the achievable cavity length of a stable DS laser based on single-mode fiber exhibiting nonlinear polarization evolution (NPE), is limited by destabilizations of mode locking regime owing to NPE "overdriving" [4]. An alternative design based on polarization-maintaining (PM) fiber and saturable absorber as a mode locker [5, 6] did not demonstrate comparably high pulse energy and short duration. Another drawback is bulk optics indispensable in these schemes [4–6].

Recent developments of all-fiber configurations based on PM fiber and mode locking by NALM (nonlinear amplifying loop mirror) [7, 8] or NPE in a short piece of SMF [9, 10] resulted in generation of stable DS with energies of up to ∼20 nJ in fibers of standard core (5.5 μm for a Nufern PM980-XP). Further energy scaling in this scheme is found to be limited by the onset of new effect, namely SRS, converting the excess energy of DSs to the noisy pulse at red - shifted Stokes wavelengths. Though in the first scheme strong destabilization was mentioned at a cavity length of ∼100 m [8], the second one demonstrated stable DS generation in longer cavities despite the presence of the Raman pulse with comparable energy [10]. Such a difference was ascribed to a weaker filtering in the last case.

Based on the analysis performed in [10], a new fiber cavity design with intracavity feedback for the Raman pulse provided by its re-injection into the laser cavity via delay loop with proper timing has been proposed and tested in [11] demonstrating formation of a coherent RDS. The RDS has characteristics similar to DS, namely the duration of ∼50 ps with linear frequency modulation (chirp) being compressible down to ∼300 fs.

Here we present the results of the main RDS parameter variations for different feedback coefficients. We found that the DS and RDS form a two-wavelength complex of coherent solitons with comparable energy and chirp. An attempt to combine DS and RDS coherently has been tried showing a perspective for building a short pulse on the base of a large number of Raman components [12].

2. Experimental setup

Figure 1 illustrates the laser scheme. The scheme consists of two functional parts. A short (2m) conventional SMF part (dotted SMF box on Figure 1) provides pulse amplification in LD-pumped active fiber as well as overdriving-free nonlinear-polarization-evolution (NPE) mode-locking controlled by both polarization controller PC and polarization beam splitter PBS having a DS output port. The rest of the cavity is a long (40 m) polarization-maintaining fiber (PMF) part providing DS formation. In such a long PMF piece the DS energy exceeds the SRS threshold and a noisy RP is formed at the Stokes-shifted wavelength. The DS and RP are split by WDM_1 and converged together after separate propagation in a Raman feedback loop. The loop

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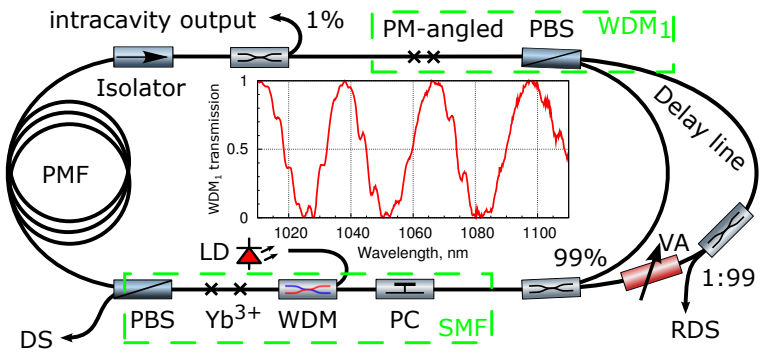

Fig. 1. The experimental setup.

provides a dispersion-compensating delay of RP as well as its re-injection into the cavity via 99% coupler of a part of RP selected by 1:99 splitter set in delay line whereas its main part is extracted from the cavity via RDS output port of the splitter. Note, that all the components are PM.

Here we have introduced several modifications as compared with the original scheme presented in [11]. First, we use standard Yb^{3+}-doped active fiber (Nufern SM-YDF-5/130) leading to generation of a DS at 1030 nm instead of 1015 nm in [11]. The WDM_2-provided "strong" filtering at $\leq$1005 nm no longer affects the DS formation. Second, our "soft" filter (WDM_1) has different parameters. It's transmission spectrum is presented as inset in Figure 1. The filter consists of a small PM-fiber piece aligned at 45° angle to the main PM-fiber axis, and a standard polarisation beam splitter (PBS) with PM fiber tails. And thirdly, a variable attenuator (VA) was introduced into the delay line of Raman feedback loop in order to study all stages of the RDS formation.

3. Results and discussion

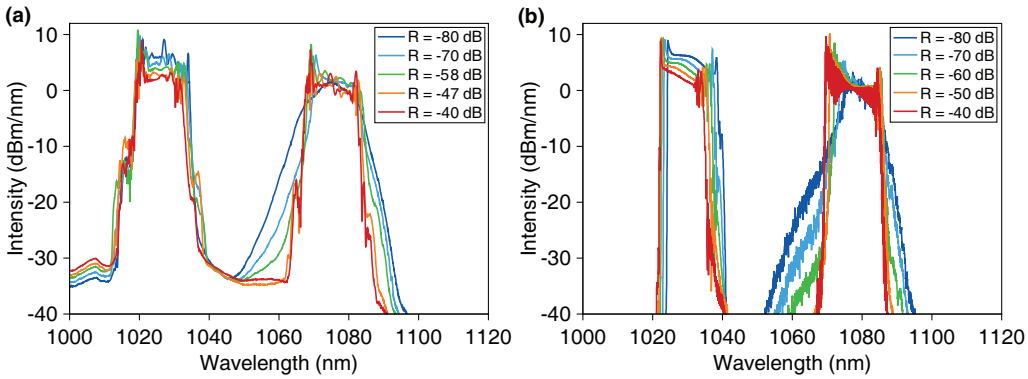

Fig. 2. Intracavity spectra in experiment (a) and simulation (b) corresponding to different feedback coefficients.

Since the Raman feedback loop is a key element in the laser scheme, we investigated in details its influence on the laser performance.

Variation of the intracavity soliton spectral shape with the feedback coefficient (R) both in experiment and simulation is presented in Figure 2. For the DS spectrum centered at ~1030 nm,

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the RP is formed at ∼1075 nm. At the value $R < 10^{-7}$, the re-injected power P_f approaches the energy of the spontaneous emission at the Stokes-shifted wavelength ($P_{sp} \sim 10^{-7}$–10^{-8}), and the feedback becomes insufficient to overcome noise. With higher feedback, the noise is eliminated and a highly chirped Raman pulse with typical M-shaped ("Batman"-type) spectrum is generated similar to the DS. At $10^{-4} < R < 10^{-2}$ and high pump level, a single DS-RDS complex splits into two similar pulse complexes separated in time. At even higher R, the two-color complex becomes too noisy and stability reduces significantly. Stable pulses in the 40-m cavity are obtained for delays in the range of 50-80 ps (with optimum at 70 ps). In the experiment the delay line was adjusted so that the RDS spectral detuning was in the range of 45–50 nm, in correspondence with the value of the Stokes wavelength shift at ∼1 μm.

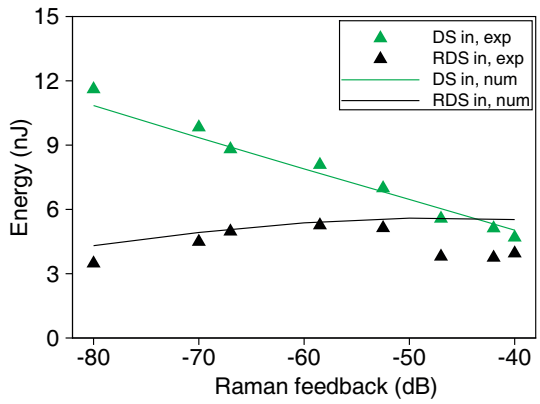

Fig. 3. Energy of the intracavity DS and RDS in the experiment (triangles) and simulation (solid lines).

The DS energy was measured at the output port of PBS, whereas the RDS energy – at the output port of the 1:99 splitter located in the delay loop. Intracavity DS and RDS energies were measured via the 1% splitter located after a PM-isolator (see Figure 1). The intracavity RDS energy grows with the feedback both in experiment and simulation. At the same time, the DS intracavity energy decreases monotonically with the feedback (Fig. 3). Note that such a monotonic behavior can only be observed if all the parameters of the experimental setup (apart from the feedback coefficient) are fixed. We found in experiment that variations of feedback at high R should be accompanied by synchronous optimization of the PC in order to retain a mode-locking regime. This explains a discrepancy between the calculated and measured energies at $R > -50$ dB. Note that the maximum intra-cavity energy of the DS depends on the feedback value $R = P_f/P = 10^{-2}$–10^{-7} logarithmically according to the equation for the SRS threshold energy, $E_{\text{th}} \approx \ln(1/R)\delta v^{-1}/g_R$, where $\delta v^{-1} = v_{DS}^{-1} - v_R^{-1}$ is the inverse group velocity difference of the DS and RDS, and g_R is the Raman gain coefficient. The estimated threshold energy for the experimental parameters without feedback is $E_{\text{th}} \sim 10$ nJ. So, on the one hand, the feedback reduces both the Raman threshold and the intracavity DS energy. On the other hand, it leads to generation of RDS and thus to a higher total energy of the DS-RDS complex.

In the next step we studied the RDS compressibility against the feedback value. The grating compressor (grating 1500 grooves/mm by Spectrogon Ltd.) length was optimized for each feedback value to minimize duration of the generated RDS. Figure 4 (a) shows the measured autocorrelation trace of the RDS. If the feedback is weak (R∼ -70 dB), the compressed pulse has a two-scale structure: a short central peak and broad noisy background. On the other hand, if the feedback coefficient is high (R∼ -40 dB), a second pulse close to the main one can be seen. Therefore, the optimum feedback, at which the maximum RDS compression factor can

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be reached is -50 dB. The full-width-half-maximum (FWHM) of the trace equals to 350 fs corresponding to 230 fs duration of a hyperbolic secant pulse.

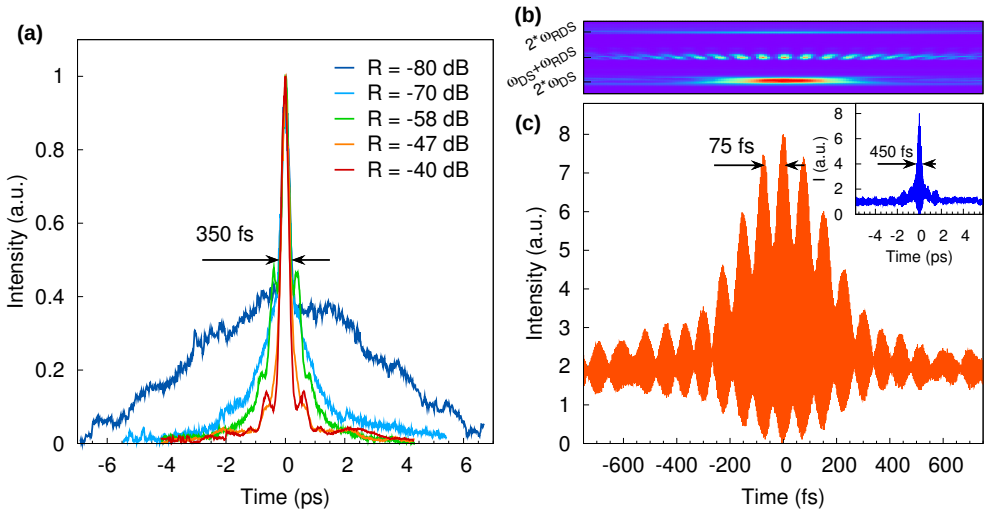

Fig. 4. Compression of RDS and coherent combining of DS and RDS. (a) Autocorrelation trace of the compressed RDS at different level of feedback. (b) FROG trace of the coherently combined DS and RDS and their cross-correlation. (c) The detailed view of the interferometric autocorrelation trace of the coherently combined pulse. Inset – the same trace in a wide range.

The final experimental step we made was verifying a possibility of DS and RDS coherent combining. The results of our numerical simulations have already demonstrated that the DS and RDS can be efficiently combined [11]. In the experiment, the DS and RDS pulses were dechirped with an external compressor and then merged together through a 50:50 coupler. The arms of the coupler were connected to the DS and RDS cavity outputs. The DS arm contains a bulk optics delay line for providing overlap between the DS and RDS. The compressor length was optimized to minimize the DS duration. Figure 4 (b,c) shows the resulted pulse. The cross-correlation shows deep modulation demonstrating high mutual coherence of the solitons. The width of the individual fringe of the interferometric trace ($\sim$40 fs) is defined by the whole spectral range of the solitonic DS-RDS complex. A period of fringes ($\sim$75 fs) corresponds to the spectral interval between DS and RDS. The width of the autocorrelation trace is 450 fs corresponding to 300 fs duration of the combined pulse. Worth noting that the fringe visibility depends on the ratio of the coherent feedback to the noise in the laser cavity. The highest coherence in calculations is reached for the feedback values $10^{-6} < R < 10^{-4}$. Note that the structure in Fig 4b remained stable for at least tens of minutes.

4. Conclusion

The modified DS-RDS laser (in comparison to [11]) with a soft filter is capable of providing an easy wavelength control of DS and RDS, since both the active fiber gain and the Raman gain spectral profiles are rather broad. Both energy and the compression factor of RDS grow with feedback and reach their optima at R=-50 – -40 dB. At optimal conditions, the output energies of DS and RDS become comparable. The resulted output energy of the two-color complex $\sim$15 nJ is slightly lower than that in [11] since the additional elements used for feedback variation insert additional losses. The compressed duration of optimized RDS is below 230 fs, comparable to

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the duration of the DS.

We experimentally proved that coherent combining of the DS and the first-order RDS is efficient and stable, holding a promise for successful combining of DS with series of further RDSs in future. Combining of RDSs of next Stokes orders will show how coherence can be preserved. Intrinsically, one can't expect extra noise of RDSs of higher orders. The approach can be considered as a way of spectral multiplexing of DSs inside the fiber laser cavity leading to high total energy, thus overcoming the SRS-induced limit for one soliton. It offers new possibilities for fundamental research as well as for applications of multi-color pulses in nonlinear microscopy [13], high-capacity coherent transmission [14] and other technologies using short-pulse fiber lasers.

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