Influence of a relaxation time of optical semiconductor saturable absorber on spectral properties of ultrashort pulses

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ABSTRACT

In the present work, the formation of ultrashort pulses in a fiber laser resonator with the effect of slow saturable absorption and spectral filtering was studied. It has been shown that in a resonator with normal chromatic dispersion, the finite relaxation time of a saturable absorber leads to a spectral shift of the generated pulses with respect to the central length of the spectral filter. The numerical results are verified using two experimental laser sources: a ring fiber laser with a semiconductor saturable absrober mirror and a fiber laser with a nonlinear amplifying loop mirror. The results obtained are relevant for designing sources of ultrashort pulses in applications for which the spectral properties of radiation are key.

Keywords: Fiber lasers, mode locking, saturable absorber, spectral filtering, dissipative solitons

1. INTRODUCTION

Begin Cavity mode-locked fiber lasers are actively used as sources of ultrashort pulses in many scientific and technological applications[1–3]. A special class of pulses, dissipative solitons, is especially important for applications that require high peak powers and optical field energies[4,5]. Dissipative solitons can have energies on the order of 10 μJ[6] and, due to the linear chirp, can be compressed outside the resonator and have a peak power up to several MW without the use of additional amplification stages[7].

Despite the progress in studying the conditions for the formation of dissipative solitons in fiber cavities, their design remains a nontrivial scientific and engineering problem[8,9]. First of all, this is due to a large number of controlled parameters of the laser system and the nonlinear dynamics of interactions of optical effects that arise during the propagation of radiation in an optical fiber, including the Kerr effect, stimulated Raman scattering, chromatic dispersion, etc. For this reason, intensive studies are being carried out to reveal the dependences of the properties of generated dissipative solitons on the parameters of a fiber resonator[10–13].

Among the studies, one can distinguish a series of works devoted to the influence of the parameters of a saturable absorber on the generation of dissipative solitons. A saturable absorber, in addition to initiating pulsed radiation, significantly affects the spectral-temporal properties of pulsed radiation due to its non-linear response. It was found[14] that a long relaxation time of a saturable absorber introduces an asymmetry into the spectral profile of the generated pulses. Further studies by the authors showed that the absorber relaxation time affects the spectral width, duration, energy, and stability of pulsed generation in a nontrivial way[15]. The depth of modulation of a saturable absorber, depending on the value of the chromatic dispersion of the resonator, can determine the conditions for stable pulse generation[16]. Finally, the shape of the dependence of the transmission of a saturable absorber on the power of transmitted pulses affects the dynamics of the change in the peak power of dissipative solitons with increasing their energy[17].

Note that most of the works considered the influence of a saturable absorber on the parameters of dissipative solitons separately from other resonator elements. In this paper, we focus our study on the mutual influence of a saturable absorber and a spectral filter on the formation of dissipative solitons in fiber resonators. Further, the conditions are determined under which the stabilization of soliton generation is due to the balance between the optical gain in the resonator and the spectral losses in the filter and saturable absorber.

2. LASER SYSTEM

On Fig.1. the scheme of the mode-locked ring fiber laser used in numerical and experimental studies is presented.

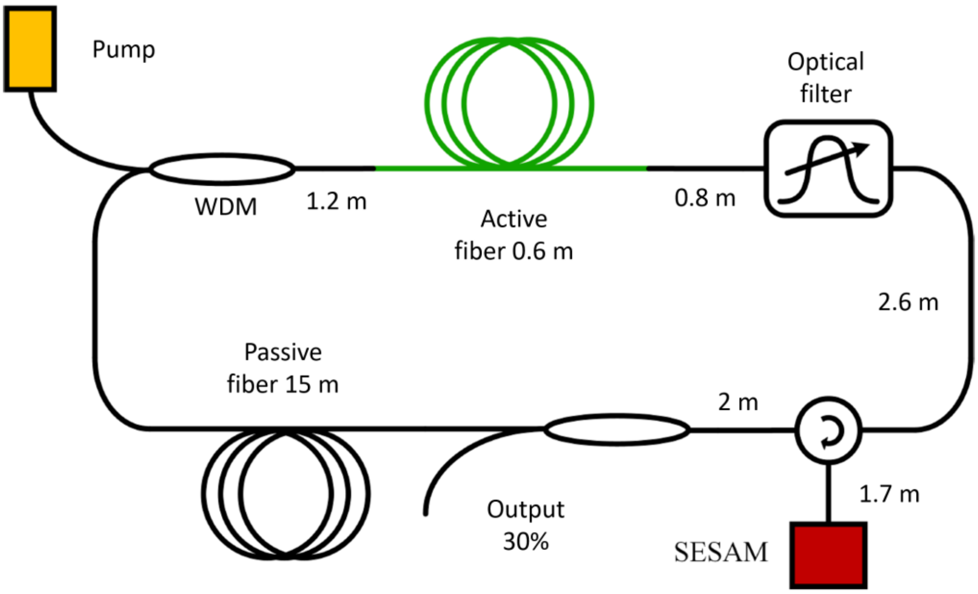


Figure 1. The scheme of a fiber ring laser resonator with a semiconductor saturable absorber mirror and a spectral filter.

The experimental scheme of the resonator included an amplifying fiber doped with ytterbium ions (light Yb 700/6) 30 cm long. The amplifying fiber was pumped by a single-mode laser diode (II-V CM96Z) with a central wavelength of 976 nm, the radiation of which was fed into the amplifying fiber using a fiber spectral combiner. Spectral filtering was provided by a tunable OzOptics BTF-100-11 filter, which made it possible to vary the bandwidth in the range from 0.2 – 18 nm and the central transmission wavelength from 1030 – 1060 nm. A PM-980 light guide with a core diameter of 6 μm and a length of 15 m was used as a passive light guide. Unidirectional propagation of radiation inside the resonator was provided by a fiber circulator, which blocked the fast polarization axis. The second port of the circulator was connected to a Batop SAM1064 semiconductor saturable absorber mirror with a relaxation time of 15 ps. 30% of the optical radiation was extracted from the resonator by a fiber coupler. All elements of the laser resonator maintained the state of optical radiation polarization. The measurement system included a 16 GHz Tektronix DPO71604C oscilloscope, a Yokogawa AQ6370D optical spectrum analyzer with a spectral resolution of 0.02 nm for optical spectrum analysis, and a PM400K5 optical power meter.

For a deeper understanding of the dynamics of pulse formation, we used a numerical model based on the numerical solution of the nonlinear Schrödinger equation (NSE), which describes the propagation of light in a medium with chromatic dispersion and the Kerr effect[18]

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A, \quad (1)$$

where A is a slowly varying envelope of the optical signal, α = 0.2 dB/km is the linear optical loss of the fiber, β_2 = 25.5 ps^2/km, γ = 4.5 W^{-1}km^{-1}. The propagation equations were solved numerically using the symmetric Fourier method of splitting into physical processes. To simulate the propagation of radiation through an amplifying fiber, a term describing the effect of saturable absorption was added to the NSE:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A + \frac{g/2}{1+E/E_{sat}}A, \quad (2)$$

where g is the differential operator, which is the Fourier transform of the Lorentzian gain profile of the fiber at a weak signal

$$g(\omega) = \frac{g_0}{1+\omega^2/\Omega^2}\ , \tag{3}$$

where g_0 is the small signal gain, ω is the circular frequency of the optical radiation, Ω is the gain spectral width, E is the pulse energy, $Esat$ is the saturation energy of the active fiber.

To calculate the absorption coefficient of a saturable absorber, we used the results of solving the following dynamic formula[19]:

$$\alpha = \frac{\partial u}{\partial t} = \frac{u_0 - u(t)}{\tau} - \frac{u(t)I(t)}{F_{sat}}u, \tag{4}$$

where u is the absorption coefficient, u_0 is the unsaturated absorption coefficient, I(t) is the intensity of the transmitted optical radiation, τ is the absorber relaxation time, F_{sat} is the absorber saturation energy.

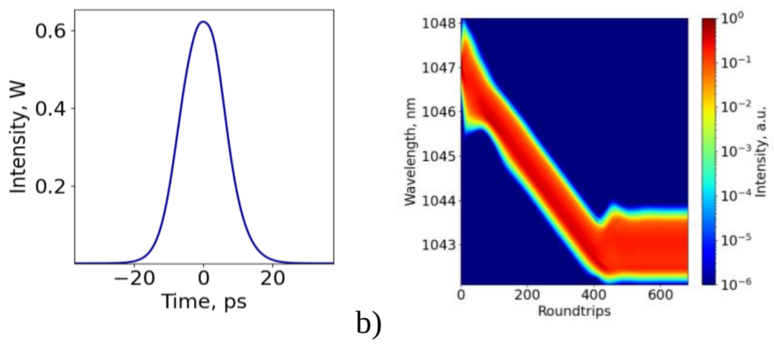
The spectral filtering was modeled by multiplying the Fourier transform of the field amplitude by the transmission function, expressed by the supergaussian function of the m_{th} order:

$$\alpha = f(\omega) = \sqrt{T_0}\exp\left(-\frac{1}{2}\left|\frac{\omega}{\Omega_{filter}}\right|^m\right), \tag{5}$$

where Ω_{filter} is the bandwidth of the spectral filter at half maximum.

3. RESULTS

In the numerical study of the laser scheme, the first step was to search for the parameters of the fiber resonator that ensure the stable generation of dissipative solitons. A stable solution was found for the following parameters: spectral filter bandwidth 9.5 nm, total cavity length 25.6 m, small signal gain 21.87 dB/m, saturation energy 13 pJ, active fiber gain bandwidth 100 nm, saturable absorber line loss coefficient 0.31, absorber saturation energy 8.7 pJ, absorber relaxation time 15 ps. The parameters of the saturable absorber were chosen based on the specification of the semiconductor saturable absorber used in the experiment. The time distribution of the solution found is shown in Fig. 2(a), the dissipative soliton FWHM was 15.18 ps. Numerical simulation made it possible to construct the evolution of the optical radiation spectrum in the process of bypassing the resonator. Fig. 2(b) demonstrates the successive spectral shift of optical radiation during the round trip of the fiber resonator up to 300 round trips, after which the shift is limited by the spectral filter and the generation of the dissipative soliton is stabilized.



a) b)

Figure 2. (a) Time distribution of a dissipative soliton (b) Evolution of the optical spectrum of optical radiation during the round trip of the laser cavity.

The mechanism of the spectral shift consists in the different transmission coefficient of the slow saturable absorber for the short and long wavelength parts of the soliton. This effect occurs due to the different temporal arrangement of the spectral components of the soliton. The leading edge of the pulse with the long-wavelength components of the soliton experiences large losses and saturates the absorber, gradually increasing its transmittance. Therefore, the short-wave components of the soliton, which are at the trailing edge of the pulse, experience smaller losses. Fig. 3. demonstrates the spectral dependence of the absorption coefficient of a spectral filter and a semiconductor saturable mirror during stable generation of a dissipative soliton. The graph also shows the optical spectrum of the dissipative soliton. Fig.3. clearly shows that the width of the optical spectrum of a dissipative soliton is determined in the short-wavelength region by the absorption profile of the spectral filter, and in the long-wavelength region by the absorption profile of the saturable absorber.

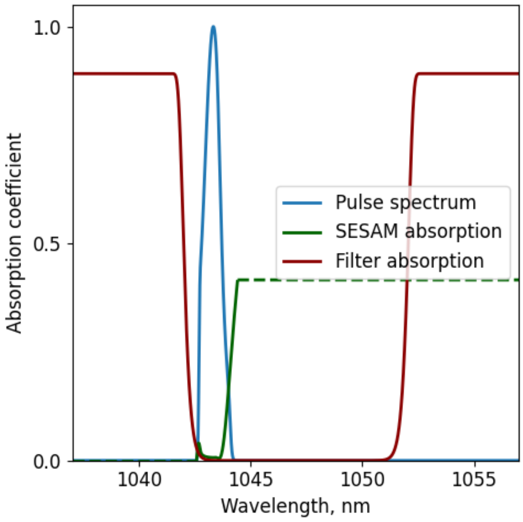


Figure 3. Spectral dependence of the absorption coefficients of an optical spectral filter (red line), a saturable semiconductor mirror (green line). The blue line indicates the optical spectrum of the generated dissipative soliton.

Note that in the case of the generation of dissipative solitons in a fiber resonator with anomalous dispersion[20], the spectral shift of the soliton to the long wavelength region is expected.

Fig. 4 shows the dependence of the spectral shift of the dissipative soliton with respect to the transmission central wavelength of the spectral filter on the relaxation time of the saturable absorber. To verify the obtained numerical results, an experimental laser system was created with the parameters of the numerical model of a ring resonator. The pulse repetition frequency was 8.1 MHz, the average radiation power was 1.23 mW. Fig. 5(a) shows the optical spectrum of a dissipative soliton generated in a ring laser cavity with a semiconductor saturable absorption mirror with a relaxation time of 15 ps. The spectral shift of the soliton relative to the central wavelength of the spectral filter was 2.73 nm.

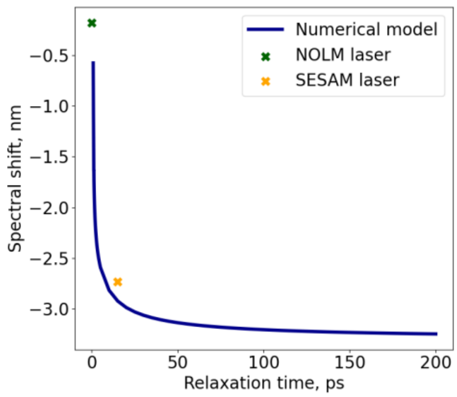
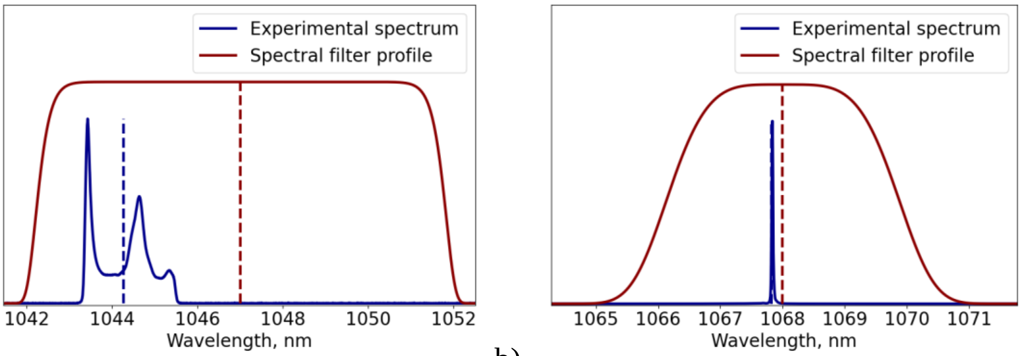


Figure 4. Dependence of the spectral shift of a dissipative soliton relative to the central wavelength of the spectral filter on the relaxation time of a semiconductor saturable absorber.

Detailed experimental verification of dependence in Fig. 4. would require a large number of saturable absorbers with different relaxation times. Therefore, we chose a fiber laser with a nonlinear amplifying loop mirror as the ultimate laser system with a fast saturable absorber. The relaxation time of the loop mirror is determined by the relaxation time of the Kerr effect, which does not exceed several femtoseconds[21]. The scheme of the laser under study is described in previous work[22]. Indeed, in the case of using a fast saturable absorber, the spectral shift of the dissipative soliton was 0.18 nm (Fig. 5 (b)).



a) b)

Figure 5. (a) The spectrum of a dissipative soliton generated in a fiber ring resonator with a slow saturating semiconductor mirror (b) The spectrum of a dissipative soliton generated in a fiber laser with a nonlinear amplifying loop mirror.

4. CONCLUSION

In this work the formation of ultrashort pulses in fiber laser cavities with normal chromatic dispersion with a slow saturable absorber and spectral filtering have been studied. The generation of dissipative solitons is demonstrated numerically and experimentally, in which the large relaxation time of the saturable absorber, which is 15 ps, leads to a spectral shift of the output optical pulses by 2.73 nm to the short-wavelength region and is limited by the bandwidth of the spectral filter. It is important to note that the found effect makes it possible to shift the spectrum of dissipative solitons to the short-wavelength region, which fundamentally distinguishes it from the effect of stimulated Raman scattering, which ensures the rearrangement of the soliton spectrum to the long-wavelength region[23]. Accounting for this effect will allow more accurate and efficient control of the spectral properties of the generated ultrashort pulses in fiber sources, where this parameter is critical.

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