Adiabatic Soliton Laser

Anastasia Bednyakova[1,2] and Sergei K. Turitsyn[1,3]
[1]Novosibirsk State University, Novosibirsk 630090, Russia
[2]Institute of Computational Technologies, Russian Academy of Sciences, Novosibirsk 630090, Russia
[3]Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, United Kingdom

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The key to generating stable optical pulses is mastery of nonlinear light dynamics in laser resonators. Modern techniques to control the buildup of laser pulses are based on nonlinear science and include classical solitons, dissipative solitons, parabolic pulses (similaritons) and various modifications and blending of these methods. Fiber lasers offer remarkable opportunities to apply one-dimensional nonlinear science models for the design and optimization of very practical laser systems. Here, we propose a new concept of a laser based on the adiabatic amplification of a soliton pulse in the cavity—the adiabatic soliton laser. The adiabatic change of the soliton parameters during evolution in the resonator relaxes the restriction on the pulse energy inherent in traditional soliton lasers. Theoretical analysis is confirmed by extensive numerical modeling.

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Introduction.—Classical optical soliton theory (e.g., [1–3] and references therein) is successfully exploited in soliton lasers [4–8], governing a generation of mode-locked, transform-limited pulses with well-defined characteristics. However, the output characteristics of traditional optical soliton lasers are restricted by the formation of spectral sidebands and multiple pulses [9]. This resonant instability imposes limits on applications of solitons in systems with periodic loss-gain perturbations, such as in fiber-optic communication systems [2] and short-pulse, mode-locked lasers [9].

Solitons in fiber lasers become unstable under the influence of resonantly amplified dispersive waves when the laser cavity length L approaches the critical length $L_{\rm cr} = 8Z_0$, in which Z_0 is the soliton period [2]. As $8Z_0 \propto T_{\rm sol}^2 \propto 1/P_{\rm sol}$ (in which $T_{\rm sol}$ and $P_{\rm sol}$ are soliton width and peak power, respectively), the stability condition $8Z_0 \geq L$ means that the instability limits the achievable smallest pulse duration and largest pulse energy. We propose suppressing resonant instability through adiabatic amplification. Therefore, eliminating the instability would allow access to the extended family of solitons of different energies and shorter pulse widths. The proposed technique may outline a new route to high-performance lasers based on cavities with anomalous dispersion.

Note that nonlinear science is critical for developing new types of lasers. New, interesting mode-locking mechanisms have been recently demonstrated to be based on exploiting various nonlinear dynamical effects in the fiber laser cavity, including the self-similarly evolving pulse [10,11] (similariton), the all-normal dispersion (dissipative soliton) generation [12–16], and more complex, hybrid nonlinear regimes [3,17,18]. These examples illustrate how nonlinear physics concepts may advance fiber laser engineering.

We propose a new concept of lasers, based on the adiabatic amplification of the soliton pulse in the cavity: the adiabatic soliton laser. The technology of adiabatic amplification of the soliton pulse was studied for signal amplification in soliton-based optical communications [19,20]. The adiabatic change of the soliton parameters during evolution in the resonator suppresses the resonance radiation of dispersive waves from the soliton inherent for traditional soliton lasers. Adiabatic amplification of the soliton in a long fiber-laser cavity could be implemented, similar to the scheme recently developed in the context of quasilossless optical-transmission links [21–24]. It is based on the distributed, second-order Raman amplification, combining bidirectional pumping at 1366 nm and fiber Bragg grating (FBG) reflectors at 1455 nm to achieve an even distribution of the gain along the fiber span at 1550 nm. In the proposed adiabatic soliton fiber laser, the distributed Raman amplifier not only compensates for losses along the cavity (as in the transmission links [21–24]), but also produces a small residual gain that is uniformly distributed along the fiber. An interesting property of the proposed scheme is that stable soliton compression can occur in the resonator.

Design of the experimental setup.—Figure 1 schematically shows the proposed design of the laser system. The ring laser cavity consists of a single-mode fiber (SMF); a 1.5-m long, erbium-doped fiber amplifier (EDFA) with normal dispersion; an output coupler with 50 percent output ratio; an optical filter with ∼2-nm spectral width centered at 1550 nm; and a saturable absorber element based on single-wall carbon nanotubes (SWCNTs) [25] that provides stable mode locking. Equal power primary pumps, operating at 1366 nm, are launched from either end of the SMF. Two FBGs with 99 percent reflectivity at

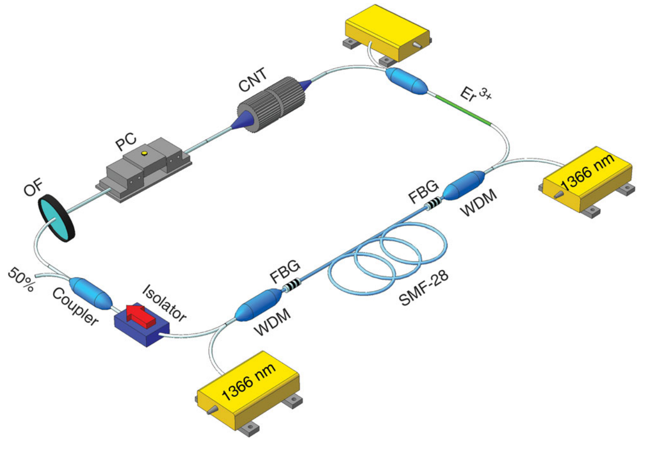

FIG. 1 (color). The experimental setup. SMF: single-mode fiber, WDM: wavelength-division multiplexer, FBG: fiber Bragg grating, OF: optical filter, PC: polarization controller, and CNT: nanotube-based saturable absorber.

1455 nm are placed at each fiber edge. The FBGs create a cavity for the radiation at 1455 nm, which serves as a secondary pump and provides evenly distributed gain for the signal at 1550 nm along the SMF. This works similarly to the ultralong laser schemes used for quasilossless transmission over long optical communication links [21–24].

The new feature in our scheme, compared to Refs. [21–24], is that the fiber span acts as a distributed adiabatic amplifier, with the output pulse power slightly higher than the input one. By comparison, in telecommunication applications that Refs. [21–24] considered, the signal input and output powers should be the same.

In the absence of Raman amplification and an optical filter, the proposed scheme represents a conventional soliton laser with the ring cavity, wherein the erbium-doped fiber is inserted into the cavity to provide a gain to the resonator [26]. The cavity length varied from 2.5 m to 8 km by means of a single-mode fiber.

Basic equations.—Signal propagation down the single mode fiber has been modeled using the nonlinear Schrödinger equation (NLSE) with gain and losses:

$$\frac{\partial A}{\partial z} = -\frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial t^2} + i\gamma |A|^2 A + gA. \tag{1}$$

Here, $A(z,t)$ is the electric field envelope, β_2 is the group velocity dispersion (GVD) at the central frequency, $\gamma = n_2\omega_0/(cA_{\rm eff})$ is the Kerr nonlinearity coefficient with the nonlinear refractive index n_2 and effective fiber cross-section area $A_{\rm eff}$ for the fundamental mode, $g = g_R - \alpha$ is the net gain coefficient, where α is the fiber attenuation coefficient, g_R is the Raman gain coefficient produced by the second-order Raman amplification scheme. The simulations are run until the pulse field reaches the steady state after a certain number of cavity round trips (the variations of the pulse peak power, width, and energy are within 1% for cavities with length less than 1 km and 7% for longer cavities). The values of the attenuation, nonlinear parameter, and dispersion of the SMF (Corning SMF-28) used in the numerical modeling were $\alpha = 0.2$ dB/km, $\beta_2 = -22.8$ ps^2/km, and $\gamma = 1.1$ W^{-1} km^{-1}.

In the lossless case $g = 0$, Eq. (1) has a solution in the form of a fundamental soliton:

$$A(z,t) = \sqrt{P_{\rm sol}}\,\mathrm{sech}(t/T_0)\exp[iz/(2L_D)], \tag{2}$$

where $P_{\rm sol} = |\beta_2|/(\gamma T_0{}^2)$ is the soliton peak power and $T_{\rm sol} = 1.763T_0$ is the soliton full width at half maximum.

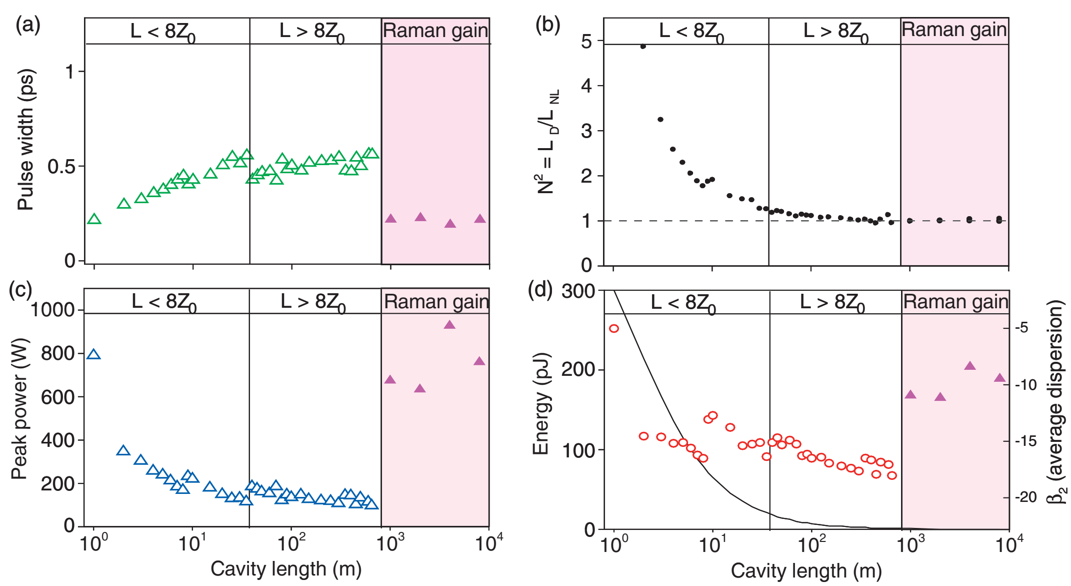

FIG. 2 (color). The calculated output pulse duration (a), soliton number (b), peak power (c), and energy (d) versus the cavity length. Black circles (c) show the soliton order N. Pink triangles show the pulse characteristics achieved with the use of adiabatic soliton amplification.

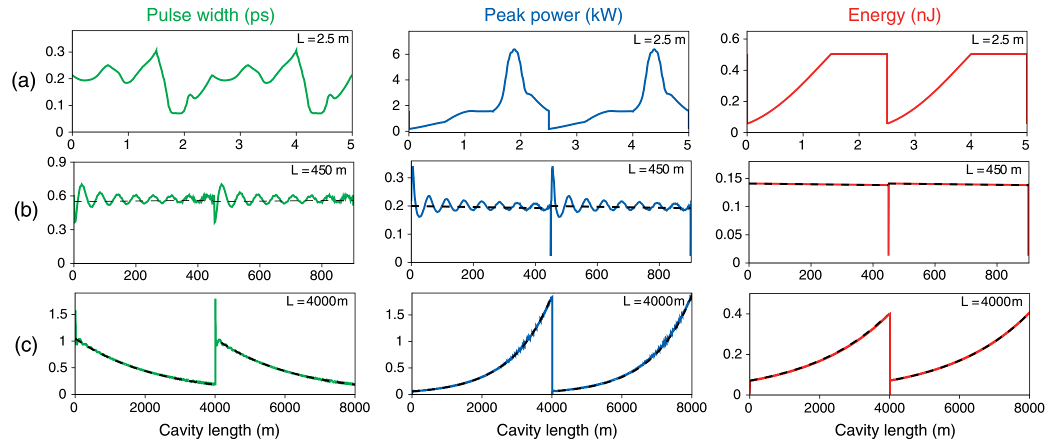

FIG. 3 (color online). Evolution of the pulse duration, peak power, and energy along the SMF for different cavity lengths: (a) 2.5 m, (b) 450 m and (c) 4000 m . The last row corresponds to the adiabatic soliton amplification along the SMF. Dashed lines show the prediction of soliton perturbation theory.

The numerical model for amplification in the 1.5-m long Er-doped active fiber uses a similar NLSE model (1), with additional accounting for the effects of gain filtering and saturation. Gain saturation depends on the total pulse energy, $g(E) = g_0/(1 + E/E_{\mathrm{satG}})$, where E is the signal energy given by $E = \int_{-T_R/2}^{T_R/2} |A(z,t)|^2 dt$, g_0 is the small signal gain coefficient of 16.6 dB/m with total gain 25 dB, $E_{\mathrm{satG}} = P_{\mathrm{satG}} T_R$ is the saturation energy, and $T_R = nL/c$ is the cavity round-trip time. The wavelength dependence of the gain is implemented in the frequency domain using the Lorentzian line shape with a bandwidth of 45 nm and a central wavelength of $\lambda_0 = 1550$ nm. The values of the nonlinear parameter and dispersion of the Erbium-doped fiber used in the numerical modeling were $\beta_2 = 12.5\ \mathrm{ps}^2/\mathrm{km}$, $\gamma = 3\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$.

In the case of a fast absorber, the intensity-dependent CNT absorption coefficient can be described as $\alpha = \alpha_0/(1 + P/P_{\mathrm{sat}}) + \alpha_{\mathrm{ns}}$, where $P = |A_{\mathrm{in}}|^2$ is the incident power of the input optical pulse, $\alpha_0 = 0.23$ and $\alpha_{\mathrm{ns}} = 0.77$ are the linear limits of saturable absorption and nonsaturable absorption, respectively, and $P_{\mathrm{sat}} = 5.3$ W is the saturation power (the power necessary to reduce the absorption coefficient to half the initial value).

Results and discussion.—Figure 2 depicts the dependence of the main pulse characteristics on the cavity length. We found that the evolution of the pulse inside the cavity can be divided into several key regimes, presented in the same figure. We proceed with three different regimes of pulse propagation for the short laser cavity (marked as $L < 8Z_0$ in Fig. 2), the long cavity (marked as $L > 8Z_0$ in Fig. 2), and the long cavity with adiabatic amplification (marked as “Raman gain” in Fig. 2).

In the first regime, for cavity length up to 15 m, pulse circulated in the cavity can be treated as a dispersion-managed (DM) soliton or stretched pulse (see, e.g., review [3] and references therein). The GVD parameter β_2 varies along the cavity following the transition between active and passive fiber dispersions, which yields to complicated intracavity dynamics of the pulse width and peak power inherent to DM solitons [Fig. 3(a), $L = 2.5$ m]. The soliton order $N^2 = L_D/L_{NL}$, calculated at the end of SMF, converges to unity with the increase of the SMF length [Fig. 2(b)]. When the length of the Er-doped fiber becomes much shorter than the SMF length, the laser can be considered as a conventional soliton laser. Similar to path average (guiding-center) solitons in optical fiber [3,18], the amplified soliton adjusts its width dynamically in the fiber section following the EDFA. However, it also sheds a part of its energy as dispersive waves during this adjustment phase. Dispersive waves are resonantly amplified when $L = 8Z_0$. Such a resonance rises up sideband

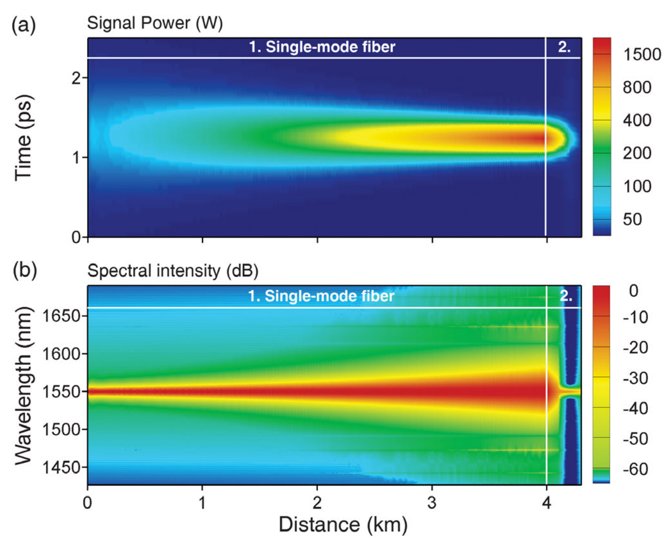

FIG. 4 (color). Evolution of the pulse shape (a) and spectrum (b) along fiber sections. Shown are the long SMF section (marked with “1”) and the short cavity section providing coupling, filtering, mode-locking and amplification of the optical pulse (marked with “2”).

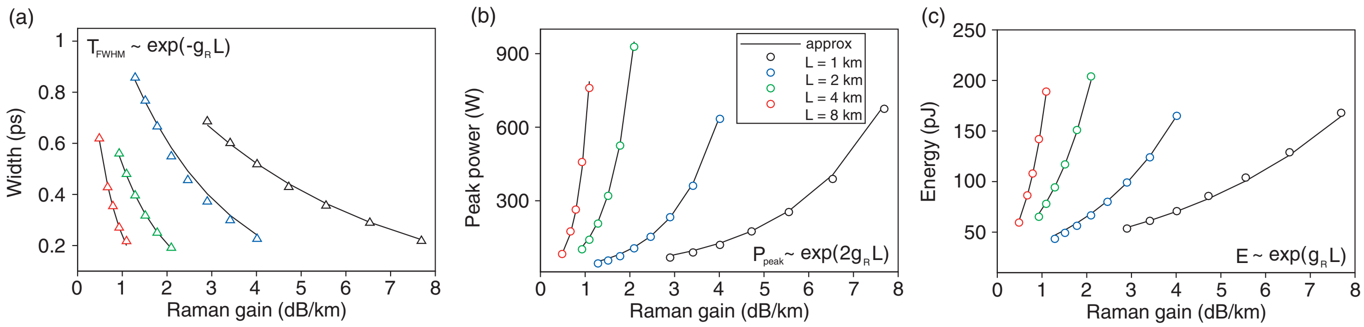

FIG. 5 (color). The calculated duration (a), peak power (b), and energy (c) of the output pulse versus the effective gain coefficient (adiabatic amplification of the soliton).

instabilities which cause the soliton to become unstable [1,9]. For stable operation of a conventional soliton laser the condition $Z_0 >> L/8$ should be satisfied, which makes a pulse width a function of a total cavity dispersion: $T_0^2 \leq L\beta_2/4\pi = \beta_2^{\text{cum}}/4\pi$.

The regime $Z_0 \gg L/8$ has been studied extensively in the context of optical soliton communications using lumped-amplification schemes (applications in which greatly reduced peak soliton powers were required) [2]. The next regime we consider is of practical interest for long mode-locked fiber lasers. We observe that in the case of $Z_0 < L/8$, solitons may evolve adiabatically, shedding dispersive waves. In this regime, it is significant that the dispersive perturbations do not destroy the soliton. We observed the regime of adiabatic (lossy) soliton propagation for cavity lengths from 37 m and beyond [see Fig. 2]. A typical feature of this regime is that the soliton pulse remains a soliton, even if the width increases exponentially along the fiber due to fiber loss [Fig. 3(b), $L = 450$ m]: $T_{\text{sol}}(z) = T_{\text{sol}}(0)\exp(-gz)$, where the Raman gain coefficient $g_R = 0$, net gain $g < 0$. Recalling that the amplitude and width of a soliton are inversely related, a broadening of the pulse leads to a decrease in soliton peak power [Fig. 3(b)]: $P_{\text{sol}}(z) = P_{\text{sol}}(0)\exp(2gz)$. Soliton order parameter N is close to 1 everywhere in the fiber. Stable pulse generation in such a long laser was observed for cavity lengths up to 700 m. For longer cavities, the lumped gain provided by EDFA does not compensate for the intracavity losses.

Adiabatic soliton laser.—To achieve stable pulse generation for longer cavities, we propose using adiabatic amplification of soliton pulses through distributed Raman amplification in an ultralong laser cavity. In the proposed laser design, EDFA gain is used to partially compensate for the lumped losses (the losses on the output coupler, filtering and unsaturated SWCNTs losses), whereas Raman gain is used to adiabatically amplify a signal along the single-mode fiber.

When the net-gain g satisfies the condition $gL_D \ll 1$, the soliton can be amplified adiabatically while maintaining $N \approx 1$, a feature that almost entirely eliminates dispersive waves. Our scheme still has gain-loss periodicity, which means that it also features spectral sidebands; however, they are greatly suppressed due to the adiabatic nature of the amplification. Steady-state evolution along the 4-km-long SMF is shown in Fig. 4. A 60-W soliton with duration of ~1 ps adiabatically compresses in the fiber: its intensity is exponentially increased $P(z) \propto \exp(2gz)$ to 1.9 kW and duration is decreased to 190 fs at the point with coordinate $z = 4$ km [Fig. 3(c), $L = 4$ km]. We can see from Fig. 3(c) that the pulse energy at $z = 4$ km is almost 6 times higher than the pulse energy at $z = 0$ km. Then, after energy loss at the output coupler, the pulse is filtered and its duration becomes adjusted to that in the beginning of the SMF. After the optical filter pulse propagates through the SWCNTs, EDFA and evolution start again in the long section of single-mode fiber.

Although the prediction of perturbation theory is accurate only for values of z, such that $gz \ll 1$ [27,28], we observe that the adiabatic soliton compression is possible up to $gz \approx 2$. At $gz > 2$ multiple-pulse generation starts to impose a limit on a pulse energy in the specific laser setup under consideration. Figure 5 shows the energy, peak power, and width of the output pulse versus the Raman gain for different cavity lengths. The energy of the soliton increases exponentially with the Raman gain growth and approaches levels that were previously unattainable in soliton lasers with long cavities.

Conclusion.—In conclusion, we have introduced a new concept of laser design known as the adiabatic soliton laser, which is based on the adiabatic amplification of soliton pulse in the resonator. The slow adiabatic change of the soliton parameters during evolution in the laser cavity relaxes the restriction on the pulse energy inherent in conventional soliton lasers. We have shown that pulse energy in such adiabatic soliton lasers is higher than in corresponding traditional soliton lasers.

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