1. INTRODUCTION

Rapidly growing nanotechnologies facilitate the creation of new compact and efficient components for laser systems. In particular, many of the latest achievements in solid-state and fiber-optic sources of ultrashort pulses owe to the progress in the technology of semiconductor saturable-absorber mirrors (SESAMs) [1, 2]. Recent experiments demonstrate, on the other hand, that, in a broad class of solid-state and fiber-optic lasers, mode locking can be implemented with the use of saturable absorbers based on carbon nanotubes (CNTs) [3–8]. Due to the advantageous combination of parameters, CNT mode lockers can easily compete with other types of saturable absorbers used in short-pulse laser sources. In contrast to nonlinear-polarization-evolution switches [9–11] and nonlinear-optical loop mirrors [12, 13], the optical response of CNT units is insensitive to the nonlinear phase shift. In addition, CNT absorbers exhibit quite fast optical response (fractions of a picosecond [14]) and can operate within a broad spectral range (from 900 to 1800 nm [5]). The saturation intensity typical of CNT absorbers is comparable to that of SESAMs. However, the laser damage threshold of CNTs is higher than that of SESAMs. Finally, an important advantage of CNT absorbers is related to the possibility of controlling their parameters by varying the CNT diameter and structure [7, 8].

One of the main disadvantages of CNT absorbers is associated with a relatively small modulation depth provided by these components (up to 10% at 1030 nm and up to 25% at 1550 nm [7]). In this context, it is of considerable interest to examine the lasing regimes enabling the generation of high-power ultrashort light pulses in laser systems including saturable absorbers with small and moderate modulations depths, as well as to understand the influence of modulation depth on the parameters of ultrashort pulses generated in such laser systems. Such an analysis is the main goal of this paper.

Below, we present numerical simulations of the dynamics of high-power self-similar light pulses in a fiber laser with a CNT-based saturable absorber. Generation of self-similar pulses, also referred to as similaritons, is of special interest for the creation of compact solid-state and fiber laser sources of high-power ultrashort pulses [15–18]. In contrast to the conventional, soliton regime of short-pulse generation, amplification of similariton pulses in a laser cavity with a positive dispersion is accompanied by pulse lengthening. However, with a carefully adjusted balance between dispersion, nonlinearity, and gain, the pulse remains self-similar, keeping a parabolic profile of its temporal envelope and a linear chirp. A similariton laser output can be compressed through a linear chirp compensation in a pulse compressor. In this paper, we identify lasing regimes in a CNT-mode-locked ytterbium-fiber laser enabling the generation of self-similar light pulses with an energy up to 330 nJ, which can be compressed to 210-fs transform-limited pulse width through linear chirp compensation in a pulse compressor. We show that, for typical parameters of a fiber laser, the bandwidth and the minimum transform-limited pulse width of a self-similar laser output are primarily limited by the small modulation depth of a CNT absorber.

2. MODEL OF A FIBER LASER WITH A CARBON-NANOTUBE SATURABLE ABSORBER

Consider a fiber laser with a ring cavity (Fig. 1) including an ytterbium-ion-doped active fiber, a passive
Here, the retarded frame of reference [24]:

$$\frac{\partial A}{\partial z} = -i \frac{\beta_2}{2} \frac{\partial^2 A}{\partial \tau^2} + i \gamma_0 |A|^2 A - \alpha A + gA. \quad (1)$$

where $\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2}$ is the propagation constant of the lasing waveguide mode, $\omega_0$ is the central frequency, $n_2 = n_2(\omega_0, cS_{\text{eff}})$ is the coefficient of nonlinearity at the frequency $\omega_0$, $n_2$ is the nonlinear refractive index of the fiber material, $c$ is the speed of light in vacuum, $S_{\text{eff}}$ is the effective mode area, and $\alpha$ is the fiber loss. Since the fiber loss (less than 1 dB/km [24]) is lower than the beam-outcoupling loss, we set $\alpha = 0$ and assume that all the linear loss is concentrated at the laser output.

The frequency dependence of the gain is approximated in our model with a parabolic profile including a saturation factor [25]:

$$g(\omega, |A(\tau, z)|^2) = \frac{g_0}{1 + W_{\text{pulse}}(z)/W_{\text{sat}}} \left(1 - \frac{\omega^2}{\Delta \Omega^2}\right), \quad (2)$$

where $W_{\text{pulse}}(z) = \int_{-\infty}^{\infty} |A(\tau, z)|^2 d\tau = \int_0^{\infty} |A(\omega, z)|^2 d\omega$ is the pulse energy; $t_R$ is the time required for a light pulse to pass through the cavity; $g_0$ and $W_{\text{sat}}$ are the pump-power-dependent small-signal gain and saturation energy, respectively; and $\Delta \Omega$ is the gain bandwidth of the active fiber. For a passive fiber, we assume that $g = 0$.

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$$g(\omega, |A(\tau, z)|^2) = \frac{g_0}{1 + W_{\text{pulse}}(z)/W_{\text{sat}}} \left(1 - \frac{\omega^2}{\Delta \Omega^2}\right). \quad (2)$$

Transformation of a light field by a pulse compressor is modeled as

$$A_{\text{out}}^G(\tau, z) = F^{-1}\left[i \omega^2 \Psi_G/2 F[A_{\text{in}}^G(\tau, z)]\right], \quad (3)$$

where $A_{\text{in}}^G$ and $A_{\text{out}}^G$ are the field envelopes before and after the compressor, $F[\cdot]$ is the Fourier transform, $F^{-1}[\cdot]$ is the inverse Fourier transform, and $\Psi_G$ is the integral second-order dispersion of the compressor. The overall cavity dispersion is thus given by $\Psi_{\text{res}} = \int \beta_2 d\tau + \Psi_G$. Beam-outcoupling radiation loss is modeled by the expression $A_{\text{out}}^C(\tau, z) = (1 - R_{\text{out}})A_{\text{in}}^C(\tau, z)$, where $A_{\text{in}}^C$ and $A_{\text{out}}^C$ are the field envelopes before and after the output coupler and $R_{\text{out}}$ is the loss coefficient, which was taken high in our simulations (see Table 1) in order to reduce nonlinearity in the passive single-mode fiber.

Since the response time of a CNT saturable absorber is estimated as a few fractions of a picosecond [14] and the modeled laser system is designed to deliver chirped pulses as long as a few picoseconds, we use a model of a fast saturable absorber in our simulations:

$$q(\tau) = q_0/(1 + |A(\tau, z)|^2/P_{\lambda}). \quad (4)$$