Investigation of hybrid modulator based on nonlinear optical loop mirror and single-walled carbon nanotubes for mode-locking in Yb-doped ultrafast fiber laser

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Abstract. Algorithm for the mathematical modelling of a fiber oscillator with a hybrid modulator based on a nonlinear fiber mirror and single-walled carbon nanotubes is suggested. It is based on a numerical solution of the nonlinear Schrödinger equation. Using numerical simulation, optimum NOLM coupler ratio, laser spot diameter on the sample preventing sample degradation and high modulator effect are determined. It is shown that hybrid modulator accelerates the self-starting process and decreases the output pulse duration up to 10%.

1. Introduction
Fiber lasers of ultrashort pulses are widely used in many fields of science and technology. The all-normal dispersion (ANDI) oscillator configuration is applied in most modern fiber systems. Such lasers are characterized by a relatively simple design with pulses energies up to several tens of nanojoules directly from the output of the oscillator[1]. Therefore, it is important to investigate and develop the new intracavity modulation methods for the stable self-starting of the pulse generation without modulator parameters degradation. Presently, the various intracavity nonlinear modulators of radiation intensity, such as effect of nonlinear polarization rotation (NPR) [2,3], semiconductor saturable absorber mirrors (SESAM) [4], nonlinear optical loop mirrors (NOLM) [5] are used for stable pulse generation in ANDI lasers. However, the mode-locking based on the single-walled carbon nanotubes (SWNT) is characterized by self-starting and is more stable than NPR and NOLM modulators. Also polymer films with SWNTs are simple for production, cheap and can be used in ring oscillator configuration, in contrast to SESAMs, which are mainly used in linear oscillator schemes. Therefore, a study of lasers with a SWNT modulator and an investigation of various modulation methods in fiber oscillators providing self-starting of pulse generation without optical degradation of the SWNT modulator are very actual problems.

In this paper the fiber oscillator with a hybrid modulator based on nonlinear optical loop mirror and SWNT is numerical simulated. The pulse duration and self-starting time dependences on the width of the spectral filter, the length of the fiber mirror, and NOLM coupler ratio are obtained. It is shown that the average power density, which optical degradation limit is 18 kW/cm², is the critical parameter for single-walled carbon nanotubes as the fiber laser modulator.
2. Numerical simulation

The effect of the hybrid modulation method based on a NOLM and a saturable absorption of SWMT was studied. An algorithm based on numerical simulation of the laser radiation propagation in single-mode optical fiber is developed for numerical simulation of fiber lasers with a hybrid modulator and determination of the optimal configuration of a modulator and a fiber oscillator. The dynamics of temporal and spectral pulses parameters of the fiber laser with an NOLM was modelled using the nonlinear Schrödinger equation. This equation is written in the form of projections onto the selected axes of the optical fiber (1) for polarization maintaining fibers. Analytical solution of this equation exists only for rare cases. The equation was solved by the standard split-step Fourier method [6].

\[
\frac{\partial A_x}{\partial z} = -\frac{\Delta \beta_1}{2} \frac{\partial A_x}{\partial T} - i \frac{\beta_2}{2} \frac{\partial^2 A_x}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3 A_x}{\partial T^3} + \frac{g_0 - \alpha_0}{2} A_x + i \gamma \left( |A_x|^2 + \frac{2}{3} |A_y|^2 \right) A_x
\]

\[
\frac{\partial A_y}{\partial z} = + \frac{\Delta \beta_1}{2} \frac{\partial A_y}{\partial T} - i \frac{\beta_2}{2} \frac{\partial^2 A_y}{\partial T^2} + \frac{\beta_3}{6} \frac{\partial^3 A_y}{\partial T^3} + \frac{g_0 - \alpha_0}{2} A_y + i \gamma \left( |A_y|^2 + \frac{2}{3} |A_x|^2 \right) A_y
\]

where \( A_{x,y}(z,t) \) is the slowly varying pulse envelope amplitude, which depends on the coordinate \( z \) of wave propagation in the fiber and on time \( t \) measured in a reference frame moving with the pulse group velocity; \( g \) is the gain in the fiber; \( \alpha \) corresponds to losses in the fiber; \( \Delta \beta_i \) - the first order group velocity dispersion, connected with birefringence of an optical fiber; \( \beta_2, \beta_3 \) are the group velocity dispersion coefficients of the second and third orders, respectively; and \( \gamma = n_2 \omega_0 / c A_{\text{eff}} \) is the nonlinear self-phase modulation coefficient (\( n_2 \) is the nonlinear refractive index, \( \omega_0 \) is the central angular frequency, \( c \) is the light velocity in vacuum and \( A_{\text{eff}} \) is the effective beam cross section).

The calculations were performed for the following fiber parameters: \( \beta_2=2.5 \times 10^{-26} \text{ s}^3/\text{m}, \beta_3=2.4 \times 10^{-41} \text{ s}^3/\text{m}, \gamma=4.7 \times 10^{-3} \text{ W}^{-1} \text{m}^1 \). The ytterbium gain spectrum was approximated by a Gaussian function with a FWHM of 40 nm and the gain maximum at a wavelength of 1030 nm [7]. Nonlinear transmittance of SWNT-carboxymethyl cellulose (CMC) composite film depending on the peak intensity is described by expression:

\[
T_{NT}(I) = T_{NS} - \frac{\Delta T}{1 + \frac{I}{I_{S,A}}},
\]

where \( T_{NT}(I) \) - sample transmittance, which depends on the intensity, \( \Delta T \) – transmittance change due to saturable absorption, \( T_{NS} \) - unsaturated part of transmittance. The saturable absorber parameters for CMC/SWNT are \( \Delta T=2.7\% \), \( T_{NS}=70.5\% \), \( I_{S,A}=0.043 \text{ GW/cm}^2 \) [8]. The values of the thresholds of optical destruction of the composite sample: the critical peak intensity (0.75 GW/cm²) and the average intensity (18 ± 1 kW/cm²) are also taken from [8].

The working model of a fiber laser with NOLM (Fig. 1 without element 8) [9] is taken as an initial scheme to optimize the parameters of the hybrid modulator of a fiber laser. Numerical simulation of this laser shows a good agreement with the experimental output characteristics. It is shown that the maximum effect on the pulse duration in the laser is provided by the NOLM and the spectral filter. For this reason, the influence of these components parameters is investigated to reduce the self-starting time.
Figure 1. Scheme of the fiber laser with NOLM: (1) PM WDM 980/1030 multiplexor; (2) 20/80 output coupler; (3) NOLM coupler; (4) NOLM fiber loop; (5) isolator–polarizer; (6) collimators; (7) spectral filter; (8) SWNT saturable absorber; (9) 10/90 coupler; (10) active Yb-doped fiber.

The numerical simulation starts from a longer pulse 600 ps with a zero spectral chirp. The calculations were continued until the laser radiation parameters (average power and pulse duration) did not change during next ten round trips along the resonator less than 0.1% (stable mode). The value inversed to resulting number of round trips was considered as the rate of the laser self-starting.

The numerical simulation shows the rate of the laser self-starting is derived from the coupling ratio in NOLM (Fig. 2a). The values of the signal part that passed through the coupler in the forward direction are plotted on the ordinate. The coupler with ratio 10/90 is marked as 90%. The laser self-starting rate dependences on the NOLM coupling ratio were obtained for the four optical fiber lengths in the loop - 10, 13.3, 16, and 20 m. The optimal ratio of the fiber coupler is in the range from 10/90 to 15/85. However, the pulse duration decreases with the coupling ratio (Fig. 2b). This effect is explained by the increasing of the NOLM modulation depth.

Figure 2. a – rate of self-starting and b – pulse duration versus NOLM coupling ratio.

The dependence of the laser self-starting rate on the fiber loop length is shown at Fig. 3a. These results were obtained for the case of a 10/90 NOLM coupling ratio. One can see that the round trips number for self-starting decreases with the fiber loop length increase. However, increasing the length of ANDI fiber oscillator leads to an increase in the pulse duration (Fig. 3b). The optimization of the fiber loop length can not be carried out in one way and determined by the pulse duration which is chosen for this laser.
The second element, which has a significant effect on the pulse duration in the considered fiber laser scheme, is an intracavity spectral filter. For numerically simulation of the spectral filter bandwidth effect on the laser self-starting rate, the 10/90 NOLM coupling ratio is taken, and the length of the fiber loop is 13.3 m. The dependence of the self-starting rate on the spectral filter bandwidth is shown in Fig. 4a. One can see that filter bandwidth increasing leads to the round trips number for self-starting decreases. The dependence of pulse duration in stable mode on the spectral filter bandwidth is shown at Fig. 4b. In Fig.4b it is shown that the output pulse duration in a stable mode increases with a spectral filter bandwidth.

For a fiber laser with a hybrid modulator (Fig. 1), the dependence of the laser self-starting rate on the peak intensity on the saturable absorber is obtained (Fig.5). In modeling radiation intensity on the sample varied due to the change of the laser beam diameter. The optimum value of the optical intensity on the sample is in the range 1-1.3 GW/cm², which is 1.5-2 times larger than the optical damage threshold (0.75 GW/cm²). The corresponding value of the average intensity for the sample with SWNTs were 300-500 kW/cm², which is 20 times higher than the threshold values (18 kW/cm²). Consequently, for fiber lasers with pulse duration more than 30 ps, the damage threshold of a modulator based on SWNT is determined by the thermal damage threshold, i.e. the average power density. The obtained results show that the optimal operation regime of a modulator based on the saturable absorber is near the thermal destruction threshold. For this fiber oscillator scheme, the threshold average intensity achieved with a laser beam diameter of 11 μm. In this case, the pulse duration in the stable generation mode is 10% less than for the case of only NOLM modulator.
3. Conclusion
The influence of various hybrid modulator parameters on the output laser characteristics was investigated using the numerical modeling based on the solution of the nonlinear Schrödinger equation. The effect of the length of the NOLM loop, the NOLM coupling ratio, the width of the intracavity spectral filter on a laser self-starting rate and output pulse duration as well as the influence of laser radiation intensity on a modulator based on SWNTs are presented. The optimum NOLM coupling ratio is from 10/90 to 15/85. The critical parameter is found to be the average intensity at the sample, the threshold value of which for the investigated sample is 18 kW/cm².

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