Khegai, Aleksandr; Melkumov, Mikhail; Firstov, Sergei; Riumkin, Konstantin; Gladush, Yury; Alyshev, Sergey; Lobanov, Alexey; Khopin, Vladimir; Afanasiev, Fedor; Nasibulin, Albert G.; Dianov, Evgeny

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*Published in:*
Optics Express

*DOI:*
10.1364/OE.26.023911

*Published: 03/09/2018*

*Document Version*
Publisher's PDF, also known as Version of record

*Please cite the original version:*

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Bismuth-doped fiber laser at 1.32 μm mode-locked by single-walled carbon nanotubes

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Abstract: Bismuth-doped fiber is a promising active media for pulsed lasers operating in various spectral regions. In this paper, we report on a picosecond mode-locked laser at a wavelength of 1.32 μm, based on a phosphosilicate fiber doped with bismuth. Stable self-starting generation of dissipative solitons, using single-walled carbon nanotubes (SWCNT) as a saturable absorber, was achieved. Evolution of the pulsed regime, depending on pump power, and stability of the pulsing were investigated.

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1. Introduction

During last decades, there has been an increased interest to pulsed lasers of different kinds. Short pulse sources operating at 1.3 μm could be attractive in various branches of science, medicine etc. A number of works demonstrated feasibility of effective use of 1.3 μm pulsed radiation in optical coherence tomography and multiphoton microscopy due to low absorption of the light by living tissues in this spectral region [1,2]. In addition, the wavelength range around 1.3 μm coincides with O-telecommunication band; therefore, pulses of this kind could be used for optic communications. Nowadays there are only bulk lasers that could be commercially realized (e.g. pulsed lasers based on Cr:forsterite or crystals with Nd) [3,4]. However, difficulties in the use and quite high price of such a systems inhibit fast development of 1.3 μm radiation-related laser applications. Therefore, there is a high demand for an ultrashort pulse source that does not have these drawbacks. Pulsed fiber lasers can easily meet the requirements but widespread silica-based rare-earth-doped active fibers are not able to provide gain around 1.3 μm. In fact, there are some fiber-based alternatives to the bulk lasers. One of them is to convert a signal of Yb pulsed source around 1.06 μm into 1.3 μm using Raman scattering or any other nonlinear conversion [2,5]. Another approach is to use ZBLAN or other soft glass active fibers doped with praseodymium ions [6]. However, both approaches are accompanied with a number of complexities that should be settled.

In recent years, development of bismuth-doped active fibers have shown significant progress. Efficient CW lasers and amplifiers based on bismuth-doped fibers were demonstrated ([7,8] and references therein). Contrary to the rare-earth elements doped silica-based fibers bismuth-doped ones do work in the region of interest. Particularly, it was shown that phosphosilicate fibers doped with bismuth can efficiently amplify an optical signal in a broad band around 1.3 μm. Besides, such active fibers can be easily spliced with standard
telecom fibers (SMF-28 or so) with minimal loss due to the fact that the core and the cladding of the bismuth fibers are made of silica-based glass.

By now, there was reported a number of pulsed lasers based on phosphosilicate fibers doped with bismuth, for example, mode-locked by SESAM [9] and using NALM/NOLM-based schemes [10]. Similar to rare-earth-doped fiber lasers the bismuth-doped fiber ones could show a self-mode-locking operation as shown in [11].

In this paper, we present a bismuth-doped fiber laser mode-locked by single-walled carbon nanotubes (SWCNTs). The use of SWCNTs is justified due to well-developed fabrication technique, easiest incorporation inside a laser scheme, compatibility with both linear and circular cavities, stable self-starting provision and so on. To the best of our knowledge, it is the first bismuth-doped fiber laser at 1.3 \( \mu \text{m} \) mode-locked by SWCNTs.

2. Experimental setup

The experimental scheme of the developed laser is presented in Fig. 1. The laser was built in well-known ring configuration. A phosphosilicate fiber doped with bismuth was chosen as an active medium of the laser. Since additional length of the fiber brings excessive nonlinearity and usually decrease a stability of the lasing, we tried to shorten the length of the active fiber. This fact is essential for bismuth-doped fiber lasers since usual gain coefficient in these fibers is much lower than that in the rare-earth doped fibers. At the same time, the section of active fiber should provide stable pulsed operation. To meet the requirements, we used the fiber sample with relatively high concentration of bismuth. A small-signal absorption of the fiber at 1.23 \( \mu \text{m} \) was about 1.5 dB/m. Corresponding net gain coefficient at the wavelength 1.32 \( \mu \text{m} \) when pumped at 1.23 \( \mu \text{m} \) was 0.32 dB/m. The length of bismuth-doped fiber was equal to 15 meters. However, such increase of bismuth concentration has resulted in rather high unsaturable loss (~0.4 dB/m at 1.23 \( \mu \text{m} \)). Although the fact affected greatly on the laser efficiency, it allowed us to shorten the length of active fiber by half in comparison with high-efficient bismuth-doped phosphosilicate fiber which gain coefficient was ~0.17 dB/m. The index difference between the core and the cladding (\( \Delta n \)) of the fiber used was mainly defined by concentration of phosphorus oxide (P\(_2\)O\(_5\)) in the core and was equal to 6.5 \( \times \) 10\(^{-3}\). The core diameter was around 6 \( \mu \text{m} \) and the fiber cutoff wavelength was equal to ~1.0 \( \mu \text{m} \). Despite we used high-concentrated sample, the bismuth ions content in the core glass was well below 0.1 wt. % (detection limit of the electron probe microanalysis) and, consequently, had negligibly small influence on \( \Delta n \) value. A Bi-doped phosphosilicate preform was fabricated using MCVD-solution doping technique. Spectroscopic characteristics of the active fibers analogous to that used in our scheme are presented elsewhere [12].
Saturable absorber consisted of thin layer of SWCNT placed between two FC/APC connectors by a dry-deposition technique [13]. A polarization controller (PC) was used to obtain a certain polarization state inside the cavity and particularly facilitated to find desirable operation mode. A fused coupler that extracted 10% of intracavity power (shown as 0.1 in Fig. 1) was placed after the active fiber to maximize output power.

Since operating wavelength is close to the zero-dispersion point of used fibers particular attention should be paid to a cavity dispersion. The total length of the laser cavity was 20 m including 15 meters of the active fiber and 5 m of SMF-28 fiber. The measurements of dispersion characteristics of the fibers used were performed with the well-known interferometric technique described in [14]. Dispersion coefficients $\beta_2$, $\beta_3$ of active fiber and SMF-28 on wavelength depicted in Fig. 1(b). The total cavity dispersion ($\beta_2$) did not exceed $10^{-2}$ ps$^2$ in the region of 1.32 $\mu$m. Rather small absolute values of the dispersion coefficient $\beta_2$ result in the effect of higher order dispersive term $\beta_3$ become comparable to the one of $\beta_2$. In addition, presence of zero-dispersion point nearby the wavelength region of the laser operation leads to the fact that the parameter $\beta_2$ changes more than 4 times in the range from 1310 to 1330 nm that is demonstrated in Fig. 1(b).

The SWCNTs sample used in our work was prepared using polymer-free aerosol technology described in [15]. The features of nanotubes and synthesis conditions were closely monitored to provide sufficient absorption at operating wavelength. In particular, an average SWCNTs diameter was ~2.1 nm that corresponds to the second van Hove optical transition ($S_{22}$) of around 1.37 $\mu$m. A spectrum of a small-signal absorption in the SWCNT module is in the inset of Fig. 2(a). An absorption band that corresponds to a $S_{11}$ transition lies in a mid-IR region (around 2.4 $\mu$m). The growth of absorption around 1.1 $\mu$m is due to the presence of metallic nanotubes. The $S_{22}$ band absorption peak was of 3.4 dB while optical attenuation at the operating wavelength of the laser was slightly less – 3.2 dB. In our case we could not use much more absorbing specimens since it would require substantial increase of active fiber length due to limited gain of Bi-doped fibers. Recovery time of the nanotubes consisted of fast and slow components associated with intraband e-e interaction and excitation transfer from semiconducting to metallic nanotube with subsequent e-ph cooling, respectively. The fast time was equal to ~0.7 ps while the slow one is 4 ps.

We have also measured nonlinear transmission shown in Fig. 2(a), the investigated sample was similar to that placed in the laser cavity (absorption at operating wavelength was about 2.5 dB). Amplified signal of the pulsed laser described below was used as a signal source for the measurement. Average power the SWCNTs was exposed to during the experiment was limited by the amplifier output power that reached 50 mW. In spite of such a high average power there was no sign of SWCNTs degradation during and after measurement. According to the experimental data modulation depth of the specimen was close to 5%.
3. Experimental results

By means of fine PC tuning a stable self-starting pulsed regime was achieved. Stochastic CW generation preceded pulsed lasing. A hysteresis of pulsed regime was characteristic of the scheme. The dependence of output power of the laser on pump power is presented in Fig. 2(b). The appropriate power thresholds for different laser regimes are indicated by arrows. It should be noted that, when pump power is above on-threshold, the pulsed laser regime including pulse duration and emission spectrum was uniquely determined by the power level providing that PC configuration was fixed.

Besides a linear signal growth, an increase in the pump power resulted in significant changes in pulse parameters. In particular, an increase of the pump power results in shortening of pulse duration from 20.5 ps down to 7.8 ps (see Fig. 3(a)) and simultaneous broadening of the spectrum as shown in Fig. 3(b). It is interesting that pulse regime remained single-pulse without additional PC adjustment until certain level of the pump power was reached. When the pump power threshold was exceeded (corresponds to 535 mW in the presented case, specific value depends on PC adjustment) the pulse mode switched to multiple pulse regime. Probably, in order to reach stable single pulse regime at powers higher than the threshold value it will be necessary to adjust PC, but in the framework of our experiments we did not succeed to make it.

![Figure 3](image_url)

**Fig. 3.** Evolution of pulse energy and duration on pump power (a); spectra of lasing at different pump powers (b); AC (c), and oscillogram (d) of the pulsed lasing.

Output characteristics of the single-pulse regime with the largest pulse energy and shortest duration obtained are depicted in Fig. 3 (b - solid line, c, d). Average lasing power was 1.15 mW. Spectrum of the pulses has steep edges and flat top, indicating that the laser generates dissipative solitons (DS) [16]. Inclined shape of the top could be caused by specific behavior of the dispersion demonstrated in Fig. 1 (b). Particularly, the effect could be explained by large relative change of $\beta_2$ within the wavelength region occupied by the pulse spectrum. Autocorrelation (AC) of the pulses is shown in Fig. 3(c). The AC profile could be well fitted with Gaussian function. The duration of the pulses according to the AC was equal to ~7.8 ps. Proceeding from the obtained spectral width and pulse duration, time-bandwidth product is calculated to be about $2.7 \text{ THz} \times 7.8 \text{ ps} = 21$ that indicated the pulses are highly chirped.
Repetition rate of the pulses of 10 MHz precisely matched the laser cavity roundtrip. According to the oscillogram depicted in Fig. 3(d) maximum deviation of the magnitude from the mean value did not exceed 3%. The pulse energy was equal to 117 pJ while peak power of the pulses calculated by stated parameters was ~15 W (150 W inside the cavity). Using the dependence in Fig. 2(b) the one can estimate the value of SWCNTs modulation depth at such a power that was equal to 1-2%. Rather small value of modulation depth required to maintain mode-locking could be explained by quite small net dispersion in the laser as well as low dispersion in each separate fiber section forming the cavity.

We have also investigated stability of the laser operation. For this aim the spectrum of output signal was monitored for 420 minutes. Figure 4 shows evolution of the output spectrum on time. Evidently, there is no remarkable difference between the obtained spectra. However, stable operation of the laser required appropriate stable pump source and fixed polarization state inside the cavity.

After that we replaced the bismuth-doped fiber used by 25 meters of the specimen with 0.2 dB/m small-signal gain. The chosen length of new fiber allowed us to keep total gain at operating wavelength almost unchanged. The total length of SMF-28 fiber was increased by 5 meters. As a result, net dispersion of the modified cavity left slightly positive. Thus, the main difference between these two cavities was an increased nonlinearity. The output spectra and AC before and after cavity modification are presented in Fig. 5(a) and Fig. 5(b). Based on the spectra in Fig. 5(a) the one can see that the laser continued generating DSs, although spectrum in the case of longer cavity was considerably narrowed. At the same time, according to the ACs of the output signals shown in Fig. 5(b) duration increased nearly twofold to 14.8 ps. Contrary to the first cavity, the second one had less stability of the lasing as well as
decreased pulse energy (84 pJ). However, the longer cavity shown better results in terms of efficiency. For example, pulsed regime depicted in Fig. 5 was obtained at a pump power of \( \approx 235 \text{ mW} \) which is nearly two times lower than that for short cavity. Thus, the use of shorter cavity offers more stability, higher pulse energy and shorter pulse duration, but lower efficiency (mainly due to higher unsaturable loss in the active fiber). At the moment, the possibility to further minimization of the cavity length is restricted by limited gain in phosphosilicate bismuth-doped fibers.

4. Conclusions

In summary, we have demonstrated, to the best of our knowledge, the first bismuth doped fiber laser mode-locked with SWCNT operating near 1.3 µm. The experimental scheme showed stable self-starting pulsed generation. The pulse energy was equal to 117 pJ while corresponding pulse duration was as short as 7.8 ps. Time-bandwidth product indicates that the pulses were highly chirped, the spectrum of the pulses had steep edges specific for DS. We suppose that obtained pulses could be compressed down to sub-picosecond durations. Variation of the cavity length showed that shorter cavity is preferable for higher stability and better pulse characteristics.

Funding

Russian Science Foundation (RSF) (16-19-10688).

Acknowledgments

The authors thank A. K. Senatorov for GVD measurements in fibers used and A. A. Krylov for fruitful discussions.

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