

DOI: 10.1070/QEL16243

Picosecond 1.3-μm bismuth fibre laser mode-locked by a nonlinear loop mirror

A.M. Khegai, F.V. Afanas'ev, K.E. Riumkin, S.V. Firstov, V.F. Khopin, D.V. Myasnikov, M.A. Mel'kumov, E.M. Dianov

Abstract. **The influence of the concentration of bismuth active centres (BACs) in phosphosilicate fibres on their optical parameters, including gain coefficient and non-saturable losses, has been studied. A range of BAC concentrations optimal for designing ultrashort-pulse (USP) lasers was chosen based on the obtained results. The optimised fibre was used to fabricate an all-fibre 1.3-μm USP laser mode-locked by a nonlinear loop mirror, which emits 11.3-ps pulses with an energy of 1.65 nJ and a repetition rate of 3.6 MHz. A bismuth fibre amplifier made it possible to increase the pulse energy to 8.3 nJ. After compression in a diffraction grating compressor, the pulse duration decreased to 530 fs.**

Keywords: *bismuth fibre laser, USP laser, lasing, mode locking, nonlinear loop mirror, non-saturable losses.*

1. Introduction

The appearance of mode-locked fibre lasers made optical ultrashort pulses (USPs) much more accessible for application in various fields, from scientific experiments to industry and medicine. This happened owing to a number of unique properties of such lasers, beginning from compactness (the size of currently available fibre USP lasers with an average power of 1 – 10 mW does not exceed the size of common smartphones) and efficiency (which reaches tens of percent) and ending with reliable operation and a rather low sensitivity to external perturbations (compared to other types of mode-locked lasers). In addition, these lasers have a rather simple design and, as a result, a relatively low cost.

At present, the most widespread USP lasers are based on fibres doped with Yb or Er ions. This is explained by convenient wavelengths of their emission (near 1.05 and 1.55 μm, respectively), as well as by high efficiency and availability of pump laser diodes. Lasers based on Tm- and Ho-doped fibres, which operate in the range of 1.75 – 2.1 μm, are also used in some special applications. Pulsed fibre lasers operating in other spectral regions can be developed either with the help of nonlinear converters pumped by rare-earth lasers or using bismuth-doped fibres, which today cover almost the entire range of 1.15 – 1.75 μm inaccessible for rare-earth lasers [1 – 4].

A very important spectral region for some applications in medicine is the region around 1.3 μm. This is explained by the fact that this region corresponds to the minimum of optical losses in such vitally important substances as water, oxyhemoglobin, and melanin, which form the basis of most biological tissues and objects of animal origin, which allows one to use radiation at 1.31 μm for medical diagnostics [5, 6].

It was previously reported on the development of USP lasers based on bismuth-doped fibres of different types emitting at wavelengths near 1.15 [1], 1.34 [2], 1.43 [3], and 1.72 μm [4]. Saturable absorbers in these lasers were either carbon nanotubes or SESAM structures. Bismuth-doped fibres based on phosphosilicate glass are suitable for operation near the 1.3-μm region of our interest. A USP laser based on this fibre with a pulse energy of 0.3 nJ and a compressed pulse duration of 580 fs was demonstrated for the first time in [2]. The use of semiconductor structures and nanotubes as saturable absorbers made it possible to ensure self-starting of the mode locking regime, but the output energy characteristics were moderate even after using a bismuth fibre amplifier [7], the pulse energy being 0.62 nJ at a pulse duration of 5.7 ps before compression.

In the present work, we report on the results of investigation of USP lasers based on bismuth-doped phosphosilicate fibres. In contrast to previous studies of bismuth fibre lasers, the Kerr nonlinearity in a fibre loop mirror was used as a mode-locking mechanism. The achieved pulse energy of 1.65 nJ at the laser output and of 8.7 nJ after the amplifier considerably exceed the results obtained in previous works using similar fibres. The pulse duration after compression by an external grating compressor was about 500 fs.

To achieve such results, we investigated the dependence of the gain and non-saturable losses on the BAC concentration and determined optimal concentrations of BACs and other dopants.

2. Study of the influence of the BAC concentration on gain and non-saturable losses

The operating efficiency of any active media considerably depends on the ratio between the level of active losses (small-signal absorption of active centres) and the level of non-saturable losses. Non-saturable losses are the losses remained in an active medium even at pump intensities considerably

A.M. Khegai, K.E. Riumkin, S.V. Firstov, M.A. Mel'kumov, E.M. Dianov Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia;
e-mail: melkoumov@fo.gpi.ru;
F.V. Afanas'ev, V.F. Khopin G.G. Devyatykh Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603950 Nizhnii Novgorod, Russia;
D.V. Myasnikov IRE-Polus Research and Technology Association, pl. Akad. Vvedenskogo 1, 141190 Fryazino, Moscow region, Russia

Received 25 October 2016; revision received 8 November 2016
Kvantovaya Elektronika **46** (12) 1077 – 1081 (2016)
Translated by M.N. Basieva

exceeding the bleaching (saturation) threshold. These residual losses can be caused by two factors, namely, by radiation attenuation unrelated to the absorption in active centres and by the absorption directly related to these centres. These losses include, for example, losses due to absorption from the excited state of active centres or structures related to these centres and the losses due to clusterization, when an active ion, which absorbed a pump photon, rapidly exchanges the energy with a neighbouring excited active centre and returns to the ground state. In this case, the pump photon energy is converted into heat and bleaching of the medium does not occur properly.

Due to absorption from the excited state, the losses in the presence of pumping may even exceed the initial level, while the attenuation unrelated to active centres never exceeds the initial level. The ratio between active and non-saturable losses (bleaching efficiency) in the best active fibres doped with rare-earth ions can reach 10^6 (for ytterbium-doped fibres) or 10^4 (for erbium-doped fibres). In bismuth-doped fibres, the maximum bleaching (~80) was achieved in germanosilicate fibres [8] and was several orders of magnitude lower than that in fibres doped with rare-earth ions. The influence of BAC concentration on non-saturable losses in bismuth-doped phosphosilicate fibres has not yet been systematically studied.

We studied several samples of bismuth-doped phosphosilicate fibres fabricated by the MCVD method. The fibre cutoff wavelength lied in the region of 1.1 μm. The difference between the refractive indices of the core and cladding Δn varied from 4.5×10^{-3} to 10×10^{-3} and was completely determined by the concentration of phosphorus in the fibre core. The BAC absorption at a wavelength of 1.24 μm was 0.05–2.4 dB m^{-1}. The absorption and gain spectra of a bismuth-doped phosphosilicate fibre are presented in Fig. 1.

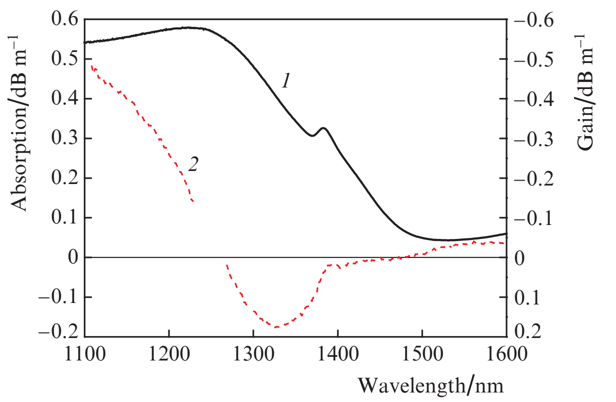

Figure 1. (*1*) Absorption and (*2*) gain spectra of the bismuth-doped phosphosilicate fibre.

The dependence of losses in the active fibre on the pump power was measured by a direct method, i.e., by measuring the radiation power coupled into the fibre and the power passed through it. To achieve a reasonable measurement accuracy, the fibre length was chosen so that the total small-signal absorption in the fibre were within the range of 10–20 dB. It was impossible to determine the absolute BAC concentration due to a low sensitivity of available microanalysis equipment and a low total bismuth concentration, as well as due to the fact that only part of introduced bismuth was active, because of which we used the absorption coefficient of the fibre at a wavelength of 1.24 μm as the relative measure of concentration. Each optical fibre was identified according to the decay level at λ = 1.24 μm. For example, BiP-1.0 means that this bismuth-doped phosphosilicate fibre has absorption coefficient α = 1.0 dB m^{-1} at a wavelength of 1.24 μm.

The measured dependences of losses on the radiation power at λ = 1.24 μm for several fibres with different concentrations of BACs are presented in Fig. 2. One can see that, with increasing pump power, the absorption in the fibre gradually decreases and then reaches a saturation level, which corresponds to non-saturable losses. It is also seen that the largest ratio between the initial and residual losses (bleaching efficiency) belongs to fibres with the initial absorption in the range of 0.18–0.6 dB m^{-1}. The fibres with absorption out of this region demonstrate weaker bleaching. In the case of fibres with absorption coefficients lower than 0.18 dB m^{-1}, the decrease in bleaching is caused by grey losses independent of bismuth, while the decrease in the bleaching efficiency in fibres with absorption exceeding 0.6 dB m^{-1} is caused by additional losses appearing due to the presence of bismuth, for example, due to the formation of bismuth clusters.

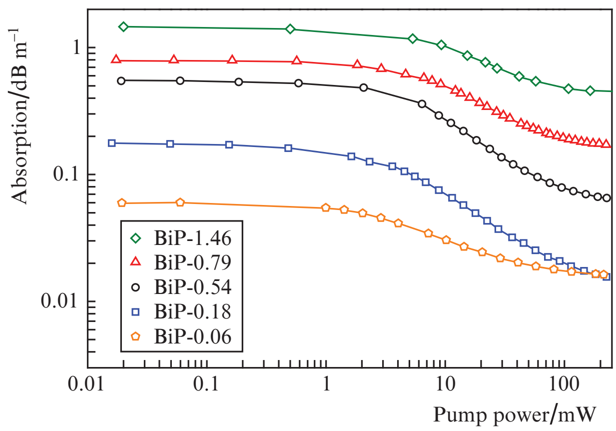

Figure 2. Dependences of absorption at λ = 1.24 μm on the signal power for fibres with different BAC concentrations.

Figure 3 shows the experimental dependences of gain coefficients G in phosphosilicate fibres with different BAC concentrations on the absorption coefficient α at λ = 1.24 μm. One can see that the maximum gain level G = 0.2 dB is achieved within the BAC absorption coefficient in the range of 0.55–1.2 dB m^{-1}. Further increase in the active bismuth concentration leads to a decrease in the gain down to negative values (i.e., to absorption). In addition, the dashed line shows the linear approximation of the G/α ratio, which changes from 0.42 to –0.1 within the considered range of BAC concentrations. It is obvious that the larger G/α, the higher lasing efficiency can be expected for a laser based on this fibre.

From the obtained data, we can conclude that, when using fibres of this type in amplifiers, one should take into account that fibres with a lower BAC concentration and, hence, with a lower gain coefficient, may demonstrate a higher efficiency of pump energy conversion into a signal due to a better bleaching of the fibre. In this case, to achieve a required total gain level, it is necessary to use a longer fibre. Fibres with

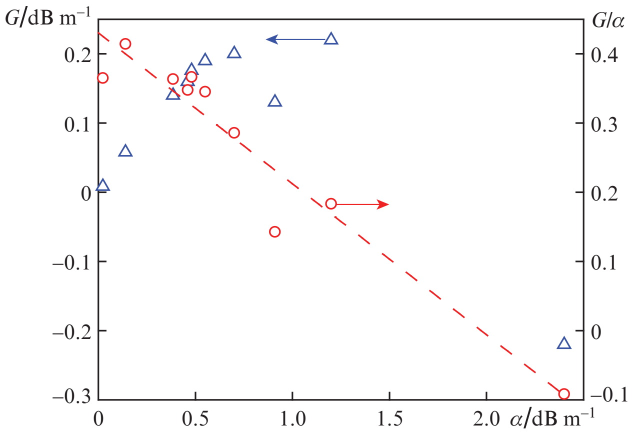

Figure 3. Experimental dependences of gain G and gain-to-absorption ratio G/α in bismuth fibres on absorption coefficient α at λ = 1.24 μm (the dashed line corresponds to the linear approximation of the G/α ratio).

higher gain per unit length require higher pump powers for complete bleaching because they have higher non-saturable losses, but the laser and amplifier lengths can be decreased.

The presented data lead to a conclusion that, for pulsed lasers and amplifiers for which a decrease in length can be an important factor, the optimal BAC concentration is the concentration corresponding to the absorption coefficient of 0.5–0.6 dB m^{-1} at λ = 1.24 μm. Based on this conclusion, we used a BiP-0.54 fibre in our subsequent work to create a pulsed laser. For applications in which the active fibre length is not so important, a higher pumping efficiency can be achieved in fibres with absorption of 0.2–0.3 dB m^{-1} at λ = 1.24 μm.

3. Bismuth laser with a wavelength of 1.3 μm

A bismuth USP fibre laser was assembled according to the figure-eight scheme presented in Fig. 4 [9–11]. The right part of the scheme consisted of a fibre loop mirror (Sagnac interferometer) and included a section of a passive highly germanium-doped fibre with a GeO_2 concentration of about 30 mol% (HiGe fibre in Fig. 4) and a polarisation controller (PC). The left part of the laser consisted of an active bismuth fibre pumped by a laser diode (LD) with a power up to 350 mW at λ = 1.24 μm via a WDM coupler, an isolator (ISO) at λ = 1.3 μm to ensure unidirectional lasing, a polarisation controller, and a 30/70 fibre coupler. The latter coupled of about 30% of laser power out of the cavity. The loop mirror and the amplifying part were connected by a 40/60 fibre coupler. As an active medium, we used bismuth-doped phosphosilicate fibre BiP-0.54 with a step refractive index profile (Δn = 5×10^{-3}). The active fibre length was about 30 m, which ensured gain of ~5 dB at λ = 1.31 μm.

To estimate the total cavity dispersion, we measured dispersion characteristics of the bismuth active fibre and of the HiGe fibre. The dispersion of SMF-28e fibre, which was used for all the other fibre components of the scheme, is also well known. The total dispersion in the scheme at a wavelength of 1.31 μm was ~0.27 ps^2 and was determined mainly by the presence of the HiGe fibre with a length of about 6 m and a dispersion of ~48 ps^2 km^{-1}, because the other fibres, including SMF-28e and bismuth active fibres, had almost zero dispersion near λ = 1.31 μm.

We measured the following radiation parameters at the output of the system: output power (Ophir Nova 2 calorimeter or Grandway FHP2 power meter), spectrum (Agilent 86140 spectrum analyser), polarisation (Thorlabs PAX 5710 polarimeter), and temporal characteristics (LeCroy WavePro7100 oscilloscope with a bandwidth of 1 GHz and INRAD 5-14B autocorrelator).

4. Experimental results

Multipulse lasing started at a pump power of about 230 mW. To achieve this, the polarisation state in the cavity was adjusted using the PC and an external action initiated the mode-locking regime from cw lasing. In this case, the width of the pulse autocorrelation function (ACF) at the laser output exceeded 100 ps. After beginning of multipulse lasing, the pump power was decreased to 180 mW, and the laser passed to a single-pulse regime with a pulse duration within the range of 10–30 ps (depending on the PC adjustment). A typical laser spectrum in the single-pulse regime is presented in Fig. 5. The sharp edges of the spectrum indicate that the laser generates dissipative solitons [12]. Sometimes, a narrow peak was recorded on the background of the broad laser line, which testified to cw lasing.

The average output power in the single-pulse regime was about 6 mW, which corresponds to a pulse energy of 1.65 nJ

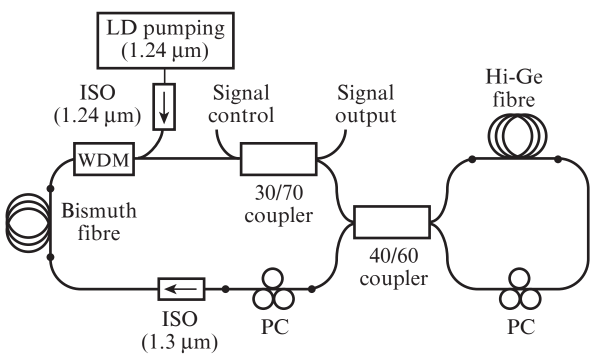

Figure 4. Figure-eight scheme of the USP bismuth fibre laser.

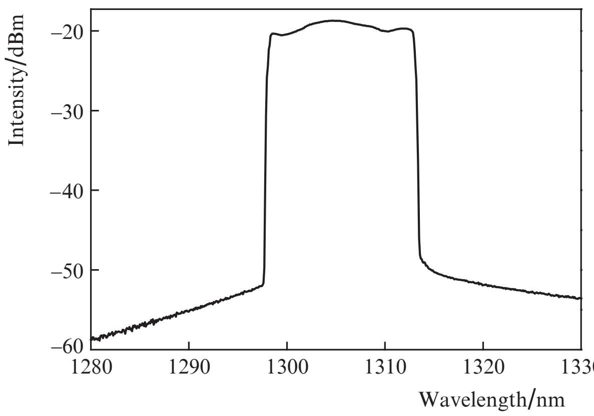

Figure 5. Laser spectrum.

at a pulse repetition rate of 3.6 MHz. The output laser linewidth was 17 nm (FWHM), and the pulse duration measured by the ACF (see the inset in Fig. 6a) was 11.3 ps (on the assumption of the $sech^2$ pulse shape). The product of the pulse duration and the spectral width was ~33.5, which indicates significant pulse frequency modulation. This allowed us to compress the pulse to a duration of ~530 fs (see the ACF in Fig. 6a) using a compressor based on reflecting diffraction gratings with a density of 600 lines mm^{-1}. From Fig. 6a one can see that pulses both at the input of the laser and after the compressor have a $sech^2$ shape and almost no pedestal.

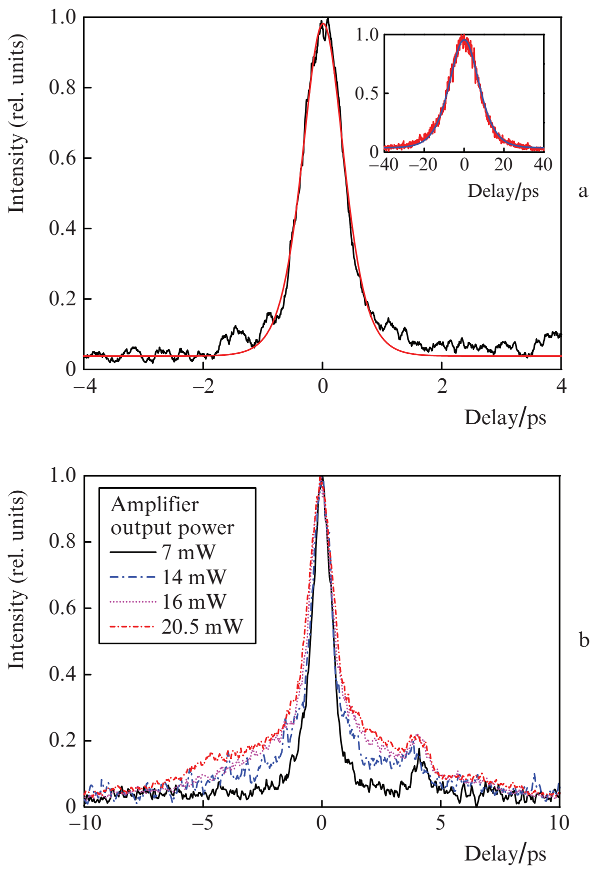

Figure 6. ACF of compressed pulses at the laser output (a) and after the amplifier at different output powers (b). The inset shows the ACF of uncompressed pulses at the laser output.

To check the possibility of increasing the pulse energy, we created a bismuth fibre amplifier pumped by two 300-mW laser diodes (1.24 μm). As an active medium, we used a BiP-0.54 fibre 200 m long. Pumping was performed from two sides via WDM. The laser radiation was coupled into the amplifier through a fibre optical isolator at λ = 1.3 μm. The average power at the output of the amplifier reached 30 mW, while the pulse energy increased to 8.3 nJ.

The pulse duration after the amplifier did not change, while the ACF was identical to the function presented in the inset of Fig. 6a. The amplified pulses were also compressed using a grating compressor. The ACFs of amplified and compressed pulses are shown in Fig. 6b for different radiation powers at the output of the amplifier. One can see that, with increasing output power, the pulse duration slightly increases and, in addition, the pedestal becomes considerably higher, which indicates a growth of the nonlinear component of the pulse frequency modulation.

5. Conclusions

As a result of this work, we fabricated a series of phosphosilicate fibres with different concentrations of bismuth active centres. The influence of the active bismuth concentration (absorption at a wavelength of 1.24 μm) on the gain properties and bleaching of the optical fibre was studied. It was found that, within the absorption coefficient range of 0.55–1.2 dB m^{-1} at λ = 1.24 μm, the gain in fibres changes only slightly and is about 0.2 dB m^{-1} at a wavelength of 1.31 μm, while the transmission of fibres considerably decreases with increasing absorption coefficient. Based on these data, we selected an optimal optical fibre for the use in USP lasers.

Using the selected fibre, we developed an all-fibre 1.3-μm USP laser with mode-locking based on a nonlinear loop mirror. The laser generated dissipative solitons with duration of 11.3 ps, pulse energy of 1.65 nJ, and pulse repetition rate of ~3.6 MHz. The average output power was 6 mW. The pulses were amplified in a bismuth amplifier with bidirectional pumping (total pump power 600 mW) to an average power of 30 mW, which corresponded to a pulse energy of 8.3 nJ. Compression of pulses with a grating compressor allowed us to decrease their duration to 530 fs.

These characteristics of subpicosecond pulses at a wavelength of 1.31 μm were obtained in bismuth-based fibre systems for the first time and are comparable with the parameters obtained previously in lasers based on praseodymium-doped fluoride fibre (duration ~650 fs, energy ~5.7 nJ [13]) and in commercial solid-state Cr:forsterite lasers (duration ~140 fs, energy ~20 nJ [14]).

Acknowledgements. The authors deeply thank M.E. Likhachev and A.A. Krylov (FORC RAS) for useful discussions and providing measurement equipment, as well as A.K. Senatorov for measuring dispersion in fibres. This work was supported by the Russian Science Foundation (Agreement No. 16-19-10688).

References

1. Dianov E.M., Krylov A.A., Dvoyrin V.V., Mashinsky V.M., Kryukov P.G., Okhotnikov O.G., Guina M. *J. Opt. Soc. Am. B*, **24**, 1807 (2007).
2. Gumenyuk R., Puustinen J., Shubin A.V., Bufetov I.A., Dianov E.M., Okhotnikov O.G. *Opt. Lett.*, **38**, 4005 (2013).
3. Gumenyuk R., Melkumov M.A., Khopin V.F., Dianov E.M., Okhotnikov O.G. *Sci. Rep.*, **4**, 7044 (2014).
4. Noronen T., Firstov S.V., Dianov E.M., Okhotnikov O.G. *Sci. Rep.*, **6**, 24876 (2016).
5. McWilliam A. *PhD Thesis* (University of St. Andrews, 2007).
6. Sun C., Chen C., Chu S., Tsai T., Chen Y., Lin B. *Opt. Lett.*, **28**, 2488 (2003).
7. Heikkinen J., Gumenyuk R., Rantamäki A., Leinonen T., Melkumov M., Dianov E., Okhotnikov O. *Opt. Express*, **22**, 11446 (2014).
8. Melkumov M.A., Bufetov I.A., Shubin A.V., Firstov S.V., Khopin V.F., Guryanov A.N., Dianov E.M. *Opt. Lett.*, **36**, 2408 (2011).
9. Duling I.N. *Opt. Lett.*, **16**, 539 (1991).
10. Avdokhin A.V., Popov S.V., Taylor J.R. *Opt. Express*, **11**, 265 (2003).
11. Nicholson J.W., Andrejco M. *Opt. Express*, **14**, 8160 (2006).

12. Renninger W.H., Chong A., Wise F.W. *Phys. Rev. A*, **77**, 023814 (2008).
13. Guy M.J., Noske D.U., Boskovic A., Taylor J.R., et al. *Opt. Lett.*, **19**, 828 (1994).
14. http://www.avesta.ru/pageseng/Cr:Forsterite-Femtosecond-LASERS/14-.htm.