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Ytterbium fibre laser with a heavily Yb^{3+}-doped glass fibre core

I.A. Bufetov, S.L. Semenov, A.F. Kosolapov, M.A. Mel'kumov, V.V. Dudin,
B.I. Galagan, B.I. Denker, V.V. Osiko, S.E. Sverchkov, E.M. Dianov

***Abstract*. The use of optical fibres with a high concentration of active ions in the fibre core allows the reduction of the active fibre length and the increase in the threshold powers of various nonlinear effects in the fibre, thereby increasing the maximum output power of fibre lasers. For this purpose, we manufactured a highly concentrated ytterbium-doped ($\sim 1.0 \times 10^{21}$ cm^{-3}) phosphate glass for the active fibre core and a pure glass of a similar composition for the fibre cladding. A single-mode fibre is fabricated from these glasses and generation is obtained in an ytterbium laser based on this fibre with the slope efficiency of no less than 60 % at a wavelength of 975 nm.**

Keywords: *fibre laser, phosphate glass, ytterbium.*

1. Introduction

The output power of single-mode fibre lasers has increased many times for the last several years and achieved ~ 2 kW in the cw regime [1]. The output power of such fibre lasers is restricted by a number of physical phenomena, in particular, by various nonlinear optical processes such as stimulated Raman scattering, four-wave mixing, etc. Because the gains corresponding to nonlinear processes are proportional to the laser-fibre length, a decrease in this length leads to an increase in the thresholds of the development of various nonlinear effects in the laser fibre, thereby increasing the maximum output power of the fibre laser. In laser fibres heavily doped with active ions, the pump power is absorbed at a small length, which allows the use of short laser fibres. Silica fibres employed in high-power lasers have a core consisting of SiO_2 with additions of Al_2O_3 or P_2O_5 and doped with ytterbium ions up to a concentration of the order of 1×10^{20} cm^{-3}. Glasses of different compositions, for example, phosphate glasses can be doped with rare-earth ions up to higher concentrations [2]. In this paper, we studied the possibilities of developing ytterbium-doped phosphate glass fibre lasers and the ways for solving technological problems involved.

2. Glasses for the fibre core and cladding

The problem of developing glasses heavily doped with active ions for the laser fibre core and glasses for the fibre cladding determined the direction of our search for a proper composition of phosphate glasses. An advantage of phosphate laser glasses over silicate glasses is the possibility of their doping with rare-earth ions up to concentrations as high as 4.2×10^{21} cm^{-3} [2] without a noticeable deterioration of the technological properties of glasses and without the formation of clusters of rare-earth ions, which strongly quench luminescence.

In this paper, we developed and fabricated multicomponent phosphate glasses for the fibre core and cladding, which are stable with respect to crystallisation and the action of atmospheric humidity. The glasses contain along with P_2O_5 (at a mass concentration of ~ 60 %) and oxides of rare-earth elements (ytterbium and lanthanum in the core glass and optically inactive yttrium in the cladding glass) also Na_2O, K_2O, CaO, BaO, SiO_2, B_2O_3. The required difference of the refractive indices of the core and cladding glasses ($\Delta n \sim 10^{-2}$) was provided by doping the fibre core with lead oxide at a mass concentration of a few percent.

At the first stage of our study we decided to limit the concentration of ytterbium in the core glass by the value 1×10^{21} cm^{-3}. This is explained by very strict requirements imposed on the degree of dehydration of glasses heavily doped with ytterbium because the quenching of ytterbium luminescence by OH^- groups, which are inevitably present in phosphate glasses, increases with increasing the Yb^{3+} concentration (see, for example, [3]).

We developed an original technology for synthesis of glasses to produce glass ingots of a high optical quality of volume 0.2 – 0.5 L. The technology included 'drying' the glass melt during its founding (the absorption coefficient of residual OH groups at a wavelength of 3.33 μm in the prepared glass did not exceed 1 cm^{-1}) so that the luminescence lifetime of ytterbium ions coincided with the radiative lifetime $\tau = 1.2$ ms.

Figure 1 presents the absorption and luminescence spectra of the developed ytterbium-doped phosphate glass. The absorption spectrum was obtained in the small-signal absorption regime. The luminescence spectrum was detected by pumping a phosphate glass fibre core of diameter 10 μm

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I.A. Bufetov, S.L. Semenov, A.F. Kosolapov, M.A. Mel'kumov, V.V. Dudin, E.M. Dianov Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: iabuf@fo.gpi.ru;
B.I. Galagan, B.I. Denker, V.V. Osiko, S.E. Sverchkov Laser Materials and Technology Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 117942 Moscow, Russia

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at a wavelength of 925 nm. To exclude the influence of reabsorption, we detected only luminescence emission propagating perpendicular to the fibre axis. The absorption coefficient of the phosphate glass at the absorption band maximum at 975 nm was 5.2 dB mm^{-1}. The main luminescence band was located at the same wavelength (within an accuracy of 1 nm). The second, broader luminescence band was located at a wavelength of 1002 nm. A weak band observed at 925 nm (Fig. 1b) was caused by scattering of pump radiation. The absorption and luminescence spectra of the phosphate glass were substantially different from the spectra of Yb^{3+} in silica fibres doped with P_2O_5 with a molar concentration of a few percent [4]. These spectra are also presented in Fig. 1. The maximum absorption coefficient of silica fibres doped with Yb^{3+} at a concentration of $\sim 10^{20}$ cm^{-3} was ~ 0.5 dB mm^{-1} at 975 nm. Although phosphorous is a substantial component both of phosphate and silica glasses, the difference in the shapes of their spectra demonstrate the different splitting of the Stark sublevels $^2\text{F}_{5/2}$ and $^2\text{F}_{7/2}$ of the Yb^{3+} ion in these glasses.

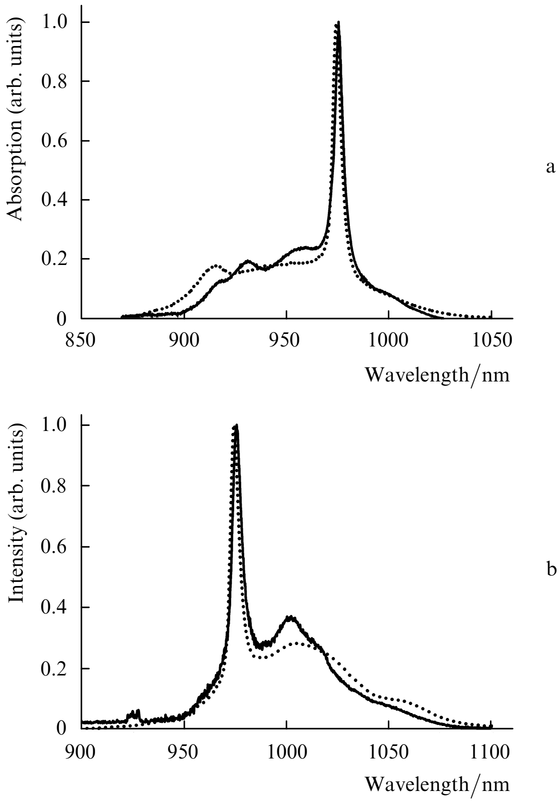

Figure 1. Absorption (a) and luminescence (b) spectra of ytterbium ions in phosphate (solid curves) glass and silica (dotted curves) glass doped with P_2O_5.

3. Optical fibre

Because glasses that were developed for the fibre core and cladding had compatible chemical and thermomechanical parameters (softening temperature and thermal expansion coefficient), it was possible to fabricate from them a nearly single-mode fibre. For this purpose, we manufactured rods of diameter 15 mm and length $\sim$ 50 mm from these glasses. At the centre of a rod made of a passive glass (without ytterbium) a hole of diameter 2 mm was drilled along the longitudinal axis. A rod made of the ytterbium-doped glass was drawn to a stick of diameter 800 μm, which was them inserted to the hole of the passive-glass rod. This construction was then drawn to a fibre of diameter 170 μm with the average diameter of the ytterbium-doped glass core equal to $\sim$ 9 μm.

Fibres were drawn in a specially developed furnace, which was optimised for working with non-silica glasses (the operating temperature was maintained in the range from 300 to 1000 °C with an accuracy of 0.5 °C). The drawing regime ($T \sim 600$ °C) was selected to eliminate the appearance of an air gap between the fibre core and cladding. No polymer coating was deposited on fibres in first experiments.

4. Laser action

We estimated the lasing properties of an ytterbium-doped fibre without a polymer coating by using the optical scheme in which single-mode (in transverse indices) pump radiation was coupled directly into the fibre core (Fig. 2). Pumping was performed with a neodymium laser at a wavelength of 925 nm [5, 6]. The $\sim$ 1-W pump power was coupled into the active fibre through a single-mode fibre with a highly reflecting ($\sim$ 100 %) 975-nm fibre Bragg grating (FBG) spliced to the pump laser output. The width of the FBG reflection spectrum was 1 nm.

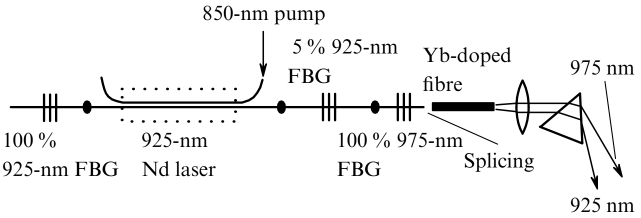

Figure 2. Scheme of the experiment.

The active element of the laser was an ytterbium-doped fibre of length 22 mm, which was chosen to provide complete absorption of pump radiation. Because the softening temperature of a phosphate glass is substantially lower than that of a silica glass, from which the fibre with the FBG was made, these two fibres could not be spliced and were simply butt-jointed, i.e., parallel end faces of the fibres were brought into contact as close as possible, the distance between them of the order of a few microns being determined by the imperfection of fibre end cleaves.

The ytterbium laser resonator was formed by the 975-nm FBG and the glass – air interface at the output end of the ytterbium fibre. Upon coupling pump radiation into the ytterbium fibre, lasing appeared at a wavelength determined by the FBG. The threshold pump power was $\sim$ 140 mW. Figure 3 shows the emission spectrum of the ytterbium laser obtained slightly above the threshold. Note that along with the narrow lines of unabsorbed pump radiation at 925 nm and ytterbium lasing at 975 nm, a rather broad luminescence band of Yb^{3+} ions is observed at $\sim$ 1010 nm. When the 975-nm FBG was absent in the scheme (Fig. 2), lasing also appeared (in this case, fibre end cleaves served as the resonator mirrors), but the emission spectrum was broader and had a maximum at 978 nm.

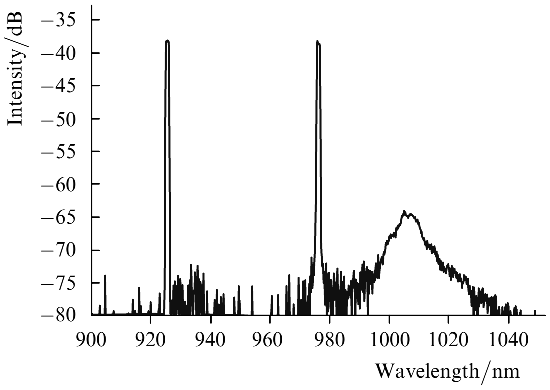

Figure 3. Emission spectrum of the ytterbium-doped phosphate glass fibre laser.

The output power of the ytterbium laser at different wavelengths was measured by transforming the output radiation by means of a lens to a nearly parallel beam, which then was dispersed with a prism into spectral components. In the scheme with the 975-nm FBG, the output power achieved 250 mW for 670 mW of pump power from the neodymium laser, the unabsorbed pump power being 125 mW. Therefore, the lasing efficiency with respect to the absorbed power was no less than 45 %, while the slope efficiency exceeded 60 %. The lasing efficiency was calculated by neglecting optical losses of radiation and lasing at fibre splices, which understates the result obtained.

Thus, we have fabricated an optical fibre based on a new laser material – a heavily doped ytterbium-doped phosphate glass. Experiments with lasers based on these fibres have demonstrated good lasing properties of this glass, which is promising for the use in fibre lasers in general and, in particular, in high-power fibre lasers.

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