

PACS numbers: 42.55.Wd; 42.55.Rz; 42.60.By
DOI: 10.1070/QE2005v035n04ABEH002926

Yb-, Er–Yb-, and Nd-doped fibre lasers based on multi-element first cladding fibres

I.A. Bufetov, M.M. Bubnov, M.A. Melkumov, V.V. Dudin, A.V. Shubin, S.L. Semenov, K.S. Kravtsov, A.N. Gur'yanov, M.V. Yashkov, E.M. Dianov

Abstract. **Single-mode cw Yb-, Er – Yb, and Nd-doped fibre lasers are fabricated by using fibres of a complicated structure (a few silica fibres in optical contact with each other are surrounded by a polymer jacket). Such a structure allows the coupling of radiation from several pump sources into one active fibre, providing an increase in the output power of the fibre laser. The Yb-doped fibre lasers with the output power above 50 W and efficiency ∼ 65 % and the 1.608-μm Er – Yb-doped fibre laser pumped to the absorption band of Yb are fabricated and studied. The Nd-doped fibre lasers based on such fibres and emitting at 0.92 and 1.06 μm are manufactured for the first time.**

Keywords: *fibre laser, double-clad fibre, ytterbium, erbium, neodymium.*

1. Introduction

The output power of cw double-clad fibre lasers has been constantly increasing in the last years. It exceeded already 600 W for lasing at the fundamental (transverse) mode [1, 2] and achieved 1 kW in the few-mode lasing regime [1]. The main advantages of high-power diode-pumped fibre lasers are their high efficiency (the plug-in efficiency above 20 %), the design simplicity and durability (compared to gas and usual solid-state lasers), and substantially less rigid requirements to the active-medium cooling due to the use of optical fibres. The attention is chiefly paid to the increase in the output power of single-mode [2, 3] and few-mode [4 – 7] lasers whose radiation can be combined in one multimode fibre to obtain 10 kW of output power [8] and more.

The active media of high-power fibre lasers are, as a rule, Yb-doped [3, 4] or Yb – Nd-doped [5] fused silica fibres. The Yb-doped fibre lasers emit in the range from 0.98 to 1.17 μm. The emission spectrum of fibre lasers can be expanded by using fibres doped with other rare-earth ions; however, the efficiency of these lasers is much lower [9].

The Er – Yb-doped fibre lasers emit at ∼ 1.6 μm. These lasers are pumped into the absorption band of Yb ions, which provides a considerably higher absorption coefficient for pump radiation from the first cladding compared to a purely Er-doped fibre because the excited Yb ions can efficiently transfer, under certain conditions, their energy to the Er ions which produce lasing.

The three-level Nd-doped fibre laser operating on the $^4F_{3/2} - {}^4I_{9/2}$ transition can expand the emission spectrum of fibre lasers to the short-wavelength region (down to 0.92 μm). It is known that usual Nd-doped fibre lasers pumped through the first cladding produce lasing on the $^4F_{3/2} - {}^4I_{11/2}$ transition at 1.06 μm in the four-level scheme. Therefore, to obtain lasing at 0.92, it is necessary to suppress amplified emission at 1.06 μm.

Until recently the efficient lasing on the $^4F_{3/2} - {}^4I_{9/2}$ transition with the output power of a few watts at room temperature was achieved only in YAG and YVO_4 crystal matrices [10]. A clad-pumped fibre laser on the $^4F_{3/2} - {}^4I_{9/2}$ transition operated only at liquid nitrogen temperature in the four-level scheme [11]. The efficient, high-power quasi-three-level lasing on the $^4F_{3/2} - {}^4I_{9/2}$ transition of the Nd^{3+} ion in a double-clad silica fibre has been achieved under normal conditions only recently [12 – 14]. The gain at 1.06 μm was efficiently suppressed in these papers by using the W-shaped profile of the refractive index of a signal fibre, introducing additional losses by fibre bending, and by selecting appropriately the type of glass for the fibre core.

It is known [15 – 18] that the fundamental mode in W-index fibres has a finite cut-off wavelength (unlike step-index fibres without the depression region). Therefore, by selecting the fibre parameters so that the cut-off wavelength for the fundamental mode would lie in the spectral range from 0.92 to 1.06 μm, one can provide the conditions for the propagation of radiation at 0.92 μm along the fibre core and the escape of radiation at 1.06 μm out of the core. The suppression of the 1.06-μm radiation can be also achieved by fibre bending and twisting. Note that the W-index fibre was first used [19] to suppress the gain band at 1530 nm in an erbium-doped fibre amplifier to achieve the gain in the S band in the region 1.48 – 1.52 μm.

The mirrors of fibre lasers can be fibre Bragg gratings (FBGs) of the refractive index written in the fibre core or dielectric mirrors deposited on the fibre ends.

High-power fibre lasers are most often based on double-clad fibres (Fig. 1). The pump radiation is coupled into the first cladding, which is usually made of fused silica and is

I.A. Bufetov, M.M. Bubnov, M.A. Melkumov, V.V. Dudin, A.V. Shubin, S.L. Semenov, K.S. Kravtsov, E.M. Dianov Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; Tel.: (095) 132 82 56; Fax: (095) 135 81 39; e-mail: iabuf@fo.gpi.ru;
A.N. Gur'yanov, M.V. Yashkov Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, ul. Tropinina 49, 603600 Nizhnii Novgorod, Russia

Received 5 November 2004
Kvantovaya Elektronika **35** (4) 328 – 334 (2005)
Translated by M.N. Sapozhnikov

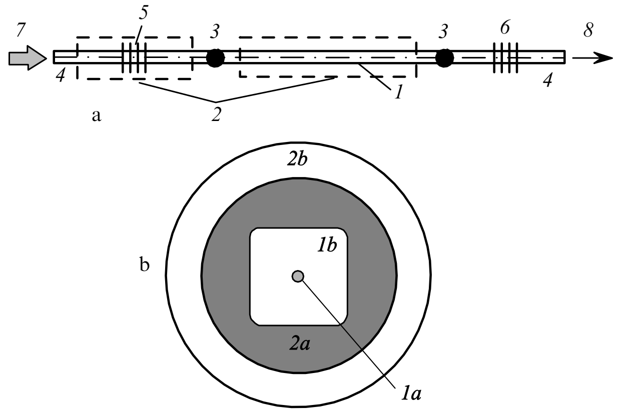

Figure 1. Scheme of a double-clad laser pumped into the end-face (a) and the cross section of a double-clad fibre (the first cladding has a square cross section) (b): (*1*) silica fibre with a core doped with active ions (*1a*: core; *1b*: first cladding); (*2*) polymer jacket (*2a*: polymer with lower refractive index (second cladding); *2b*: protective jacket); (*3*) splices of the laser fibre with fibre (*4*) in which a FBG is written; (*5*) highly reflecting FBG; (*6*) output FBG; (*7*) pump radiation; (*8*) output laser radiation.

surrounded by the second cladding with a lower refractive index. The second cladding can be made of a polymer or fused silica doped with fluorine. The first cladding is a multimode waveguide for the pump radiation. The pump radiation propagating in the first cladding is absorbed by active ions doped into the fibre core.

2. Methods for coupling pump radiation into the first cladding of a laser fibre

At present, there exist several methods for coupling pump radiation into a double-clad laser fibre:

(i) Direct coupling pump radiation through the fibre end-face (Fig. 1); in this case, the second end-face of the fibre is used to couple radiation out. The pump radiation can be also coupled through both end-faces of the double-clad fibre [1], which allows the doubling of the coupled power. However, this requires the use of non-fibre elements such as lenses and multilayer mirrors, which complicates substantially the laser design and reduces its reliability.

(ii) Coupling pump radiation through the fibre side surface by using a V-groove [20]. This method is technologically complicated and restricts the energy coupled into the fibre because only half the fibre cross section is used.

(iii) Coupling pump radiation through the fibre side surface (this method is used, as a rule, in block solid-state lasers) without using light-guiding properties of the first cladding [21]. It seems that this method can be employed only for multimode fibres because of a weak absorption of pump radiation in single-mode fibres.

(iv) Coupling radiation through the fibre side surface by using multimode couplers [22]. Such devices have several multimode inputs and one multimode output with a large aperture and a large diameter compared to input fibres and represent several fibres spliced into one. These commercial devices have low losses; however, they cannot operate at high pump powers (no more than 20 W per each fibre) and substantially reduce the radiation brightness (by half and more). The realisation of such devices was reported only in few papers [22, 23], which is probably explained by technological problems encountered in their fabrication. It is possible that a further improvement of these devices will allow one to use them in high-power fibre lasers.

(v) Coupling pump radiation by using a double-clad fibre in which, unlike the fibre in Fig. 1, the first cladding consists of several fibres (Fig. 2). Below, we will refer to such fibres as multi-element first cladding fibres (MFC fibres or GTWave fibres [24]).

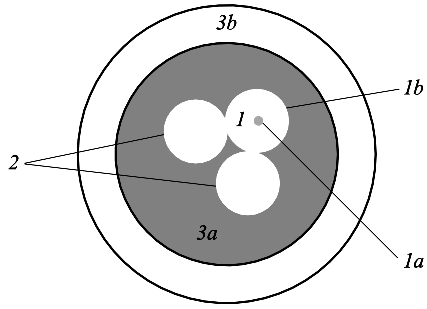

Figure 2. Cross section of an MFC fibre: (*1*) signal fibre (*1a*: core; *1b*: first cladding); (*2*) passive fibres; (*3a*) common cladding with lower refractive index; (*3b*) protective jacket.

An MFC fibre consists of an active (signal) fibre in optical contact with one or several parallel multimode silica fibres. All the fibres are surrounded by a common polymer jacket with the refractive index that is lower than that of fused silica. The cross section of a three-element fibre is shown in Fig. 2. All the separate multimode fibres (elements) are optically coupled with each other, representing the first (outer) cladding of the signal fibre core. Because multimode fibres are not mechanically coupled with each other (being combined only inside a polymer jacket), they can be separated from each other and spliced independently with passive fibres through which pump radiation is coupled, while the active fibre can be spliced with single-mode fibres for coupling and coupling out laser radiation.

The structure of MFC fibres makes it possible to assemble both all-fibre lasers (Fig. 3a), by splicing fibres with written FBGs to the active fibre ends, and fibre amplifiers by providing a convenient access to both outputs of the active fibre. Fibre schemes assembled from MFC fibres can contain several sites for coupling pump radiation (two-element fibre has two coupling sites, three-element fibre – four sites, etc.), which allows one to sum up pump powers coupled at different sites and construct high-power fibre lasers.

Another substantial advantage of MFC fibres over usual double-clad fibres is their asymmetric cross section (Fig. 3). Unlike double-clad fibres, in which, as a rule, a square (or rectangular, hexagonal, D-shaped, etc.) cross section of the first cladding is used to provide efficient absorption of light in the fibre core [25], the cross section of signal and passive fibres in MFC fibres can be circular. This substantially simplifies fibre splicing itself and reduces splicing losses at sites of splicing of the signal fibre with fibres with written FBGs.

Therefore, the structure of MFC fibres is very promising for various applications. In this paper, we report the fabrication of Yb-, Er–Yb-, and Nd-doped fibre lasers based on fibres of this type. In particular, we built Yb lasers

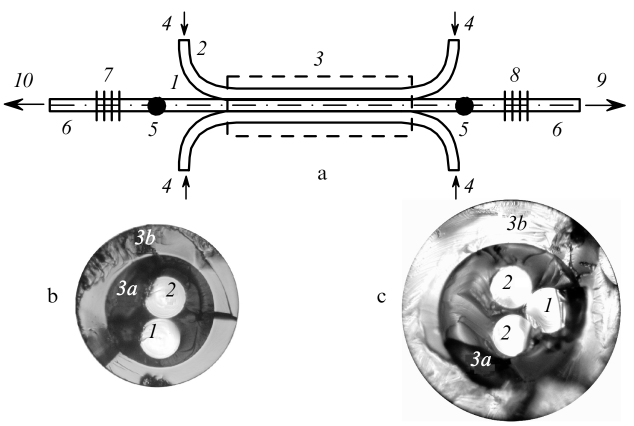

Figure 3. Scheme of a laser based on a three-element first cladding fibre (a) and photographs of the cross sections of two-element (a) and three-element (c) first cladding fibres: (*1*) signal fibre; (*2*) passive fibre; (*3*) common jacket (*3a*: cladding with lower refractive index; *3b*: protective jacket); (*4*) pump radiation; (*5*) splices of the signal fibre with fibre (*6*) in which a FBG is written; (*7*) highly reflecting FBG; (*8*) FBG with the reflectivity $\sim 5\,\%$; (*9*) output laser radiation; (*10*) laser radiation transmitted through the highly reflecting FBG.

based on two- or three-element first cladding fibres emitting in the region from 1057 to 1085 nm, Er–Yb lasers based on two-element first cladding fibres emitting at 1608 nm and Nd lasers based on two-element first cladding fibres emitting at 0.92 and 1.06 μm.

3. Yb-doped fibre lasers with the output power above 50 W

The two- and three-element first cladding laser fibres were fabricated at the Fiber Optics Research Center, A.M. Prokhorov Institute of General Physics, RAS in cooperation with the Institute of Chemistry of High-Purity Substances, RAS. One of the fibres of the MFC fibre had a fused silica cladding doped with rare-earth elements. Other fibres had no cladding and consisted completely of pure Suprasil F-300 fused silica. Individual fibres were assembled to the MFC fibre directly during fibre drawing. The second cladding, which was common for all the fibres, was made of a polymer with a lower refractive index and provided the numerical aperture ~ 0.39 for radiation propagating in the first cladding. The coupling length between the passive fibre and the first cladding of the signal fibre was about of 0.5 m.

Yb-doped fibre lasers were based on two- and three-element first cladding fibres with an alumo- or phosphosilicate core [26]. The diameter of each silica fibre inside the MFC structure was 125 μm. The diameter of the signal fibre core was from 4.4 to 11.5 μm in different lasers. Pumping was performed at ~ 978 nm by NewOptics pigtailed diode modules emitting the line with the FWHM of ~ 6 nm. The maximum power of each module at the output of the fibre with the core diameter of 200 μm and the numerical aperture of 0.22 achieved ~ 35 W. Pump radiation was coupled to passive fibres of the MFC structure through fibre tapers providing matching between the apertures and diameters of the fibres.

When the two-element first cladding fibre was used, the laser had two sites for coupling pump radiation, in the case of the three-element first cladding fibre, it had four coupling sites. The laser resonator was formed by a pair of FBGs with reflectivities $\sim 100\,\%$ and $\sim 5\,\%$. The widths of the reflection spectrum of highly reflecting FBGs at the -10-dB level were 0.8–3 nm. FBGs were written in the core of a single-mode fibre. The resonator lengths were selected in accordance with the absorption coefficient for pump radiation and were in the range from 25 to 50 m. The laser wavelength was in the range from 1057 to 1085 nm.

Despite the high reflectivity ($\sim 99.9\,\%$) of the FBG at one of the ends of the resonator, a considerable part of the laser radiation power (10 % and more) was transmitted through the grating. This is explained by the fact that, due to nonlinear effects and especially four-wave mixing, the emission spectrum of the laser becomes broader than the reflection spectrum of the FBG.

We measured the output characteristics of lasers with the mode-field diameter $D_{\rm mfd} = 6.8$ and 8.0 μm. The dependences of the laser output power and the power of radiation transmitted through the highly reflecting FBG on the pump power for lasers based on the three-element MFC fibre are presented in Fig. 4. The laser resonator based on the fibre with $D_{\rm mfd} = 6.8$ μm was formed by the highly reflecting FBG with the spectral width $\Delta\lambda \sim 1$ nm and a perpendicular cleaved fibre (the reflectivity $\sim 3.5\,\%$; denoted by A). The fibre with $D_{\rm mfd} = 8.0$ μm was used in lasers with three different resonators: the resonator formed by the 100 % FBG with $\Delta\lambda \sim 1$ nm and a perpendicular fibre end cleave (B), the resonator formed by the 100 % FBG with $\Delta\lambda \sim 1$ nm and 5 % FBG (C), and the resonator formed by the 100 % FBG with $\Delta\lambda \sim 3$ nm and 5 % FBG (D).

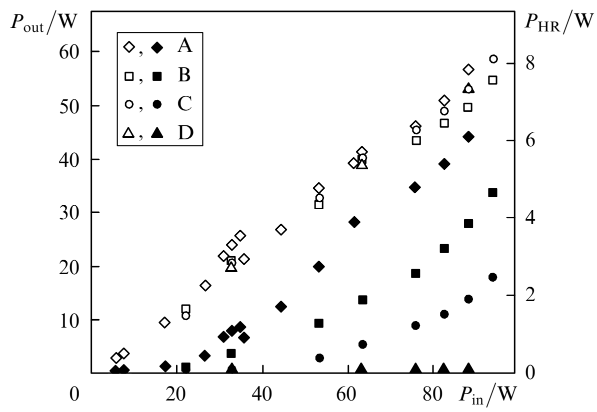

Figure 4. Dependences of the output laser power $P_{\rm out}$ (open points) and the radiation power $P_{\rm HR}$ transmitted through a highly reflecting FBG (dark points) on the pump power $P_{\rm in}$ for different lasers based on a three-element first cladding fibre; (A) laser with $D_{\rm mfd} = 6.8$ μm without a FBG at the output fibre end-face; (B) laser with $D_{\rm mfd} = 8.0$ μm without a FBG at the output fibre end-face; (C) laser with $D_{\rm mfd} = 8.0$ μm with a 5 % FBG at the output fibre end-face; (D) laser with $D_{\rm mfd} = 8.0$ μm with a highly reflecting FBG with $\Delta\lambda \sim 3$ nm and a 5 % FBG at the output fibre end-face.

One can see from Fig. 4 that the increase in the mode-field diameter results in the decrease in the power of radiation transmitted through the highly reflecting FBG. The lost power also decreases when a FBG is present at the output end of the resonator or a highly reflecting FBG with a broader reflection spectrum is used. The maximum output power achieved 60 W for the efficiency with respect to the pump power equal to $\sim 65\,\%$.

Figure 5 shows the normalised emission spectra of the laser obtained for each of the schemes considered above. One can see that, as the mode-field diameter increases and the other parameters of the laser are changed, the power of radiation transmitted through the FBG decreases and the width of the emission spectrum narrows down. Except of the above-mentioned broadening of the spectrum, we did not observe in our experiments any manifestations of other nonlinear effects such as SRS and SBS.

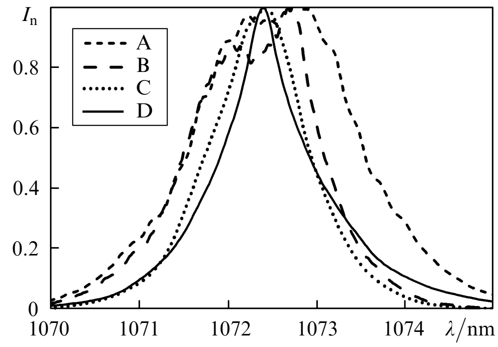

Figure 5. Normalised emission spectra of Yb-doped fibre lasers based on a three-element first cladding fibre (the A – D notation as in Fig. 4).

We estimated the influence of the output laser power on highly reflecting FBGs by measuring the emission spectra of the laser for different output powers (Fig. 6). The reflection spectrum of the FBG shifted to the red with increasing the output power. The maximum spectral shift was ~ 0.2 nm for the output power of 57 W. In this case, ~ 6 W of radiation was transmitted through the FBG. It is obvious that the reflection spectrum shifted to the red due to FBG heating by laser radiation. It was found out experimentally that the shift of the reflection spectrum of the FBG by 0.2 nm corresponds to its heating by $\sim 20\,^{\circ}$C.

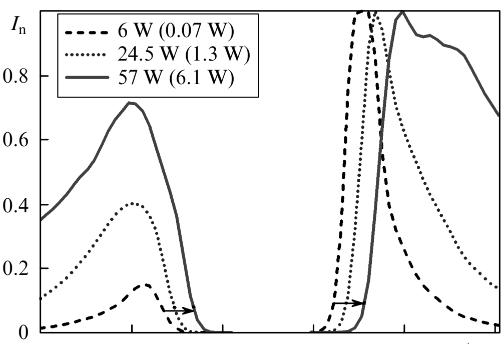

Figure 6. Normalised emission spectra of the Yb-doped fibre laser based on a three-element first cladding fibre recorded behind a highly reflecting FBG for different output powers of the laser (radiation power transmitted through the FBG is indicated in the parentheses). The arrows show the shifts of the reflection spectrum of the highly reflecting FBG.

4. Er^{3+} – Yb^{3+}-doped fibre lasers

Although the Er^{3+} ions have the absorption band at 0.98 μm, it is difficult to pump efficiently through the first cladding at this wavelength the fibre doped only with erbium ions because, as a rule, it is impossible to dope the fibre core with Er^{3+} ions up to the concentration required for the efficient absorption of pump radiation from the first cladding by preserving simultaneously the acceptable optical losses. Additional doping Er-doped fibres with Yb^{3+} ions considerably increases the absorption of pump radiation from the first cladding (up to a few dB m^{-1}) by preserving optical losses at a sufficiently low level (tens of dB km^{-1}). Upon such doping, the pump radiation is mainly absorbed by Yb^{3+} ions because they can be doped up to concentrations an order of magnitude higher and their absorption cross section at 0.975 μm is 5 – 10 times higher than that of the Er^{3+} ions. The excited Yb^{3+} ions transfer their energy to Er^{3+} ions at lasing transitions. Therefore, fibres co-doped with Er^{3+} and Yb^{3+} ions are pumped as Yb-doped fibre lasers.

The Yb $\rightarrow$ Er energy transfer efficiency depends on the glass type (phosphosilicate, alumosilicate, etc.) and on the absolute concentrations of the Yb^{3+} and Er^{3+} ions. As a rule, the energy transfer efficiency increases with decreasing the distance between the active ions in a matrix. The output power of the Er – Yb laser substantially depends on the time of relaxation of Er^{3+} ion from the $^4I_{11/2}$ level to the upper $^4I_{13/2}$ laser level, increasing at shorter relaxation times. In turn, the relaxation time depends on the maximum energy of phonons in a glass matrix, decreasing as the maximum phonon energy increases. From this point of view, a phosphosilicate glass matrix, in which the maximum phonon energy (~ 1330 cm^{-1}) exceeds this energy for an alumosilicate matrix by a factor of three, is more suitable for high-power lasers.

We fabricated several lasers based on two-element MFC fibres with the phosphosilicate core doped with Er^{3+} and Yb^{3+} ions at different concentrations. The diameter of each of the silica fibres inside the MFC structure was 125 μm. The lasers were pumped by the same source as in case of Yb-doped fibre lasers. The pump radiation was coupled only from one side through a passive fibre toward the output radiation. In some cases, to increase the absorption of the pump power, the ends of the passive and active fibres of the MFC structure from the side opposite to the pump coupling were spliced with each other to provide the return of pump radiation to the laser (Fig. 7). [This is equivalent to the use of the output mirror reflecting pump radiation back to the fibre in usual double-clad fibre lasers (see, for example, [27]); in this case, a FBG is written in the double-clad fibre core.] The scheme with the return of unabsorbed pump radiation provides a more uniform absorption of the pump and, hence, a more homogeneous distribution of excited ions over the laser length compared to the case of a standard double-clad fibre without a mirror returning pump radiation.

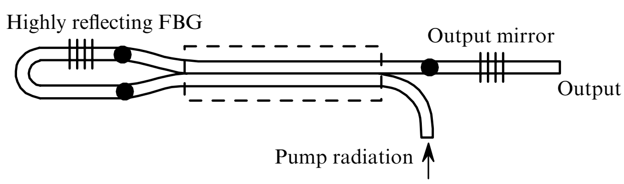

Figure 7. Scheme of a laser based on a two-element first cladding fibre with returned pumped radiation.

The resonator lengths were selected according to the absorption coefficient for pump radiation and were from 7 to 25 m, while the resonators themselves were formed by a 1608-μm highly reflecting FBG on the one side and a perpendicular fibre cleave or a weakly reflecting FBG on the other side.

The parasitic lasing and superluminescence of the Yb^{3+} ions were suppressed by minimising the feedback for radiation different from the 1608-nm radiation. For this purpose, to the fibre behind the highly reflecting FBG, a fibre without a core was spliced whose end was immersed into glycerol.

Figure 8 shows the output power of 1.6-μm Er–Yb lasers based on different fibres with the resonator length $L_c = 8$ and 15 m as a function of the 0.97-μm pump power. The mass concentration of Yb^{3+} (Er^{3+}) ions in the lasers with $L_c = 8$ and 15 m was 2.2 (1.0) % and 1.6 (0.3) %, respectively. One can see that the efficiency of both lasers is almost the same and is $\sim 20\,\%$. It seems that such a low efficiency (lower by a factor of three than the quantum efficiency) is caused by the presence of Yb^{3+} ions in the fibre core that do not transfer their energy to Er^{3+} ions, which is manifested in the appearance of superluminescence and, as the pump power is increased, in lasing of Yb^{3+} ions in the range from 1.05 to 1.06 μm despite the attempts to suppress the feedback. The presence of a great amount of Yb^{3+} ions (estimated as 10 % – 50 %) that do not transfer their energy to Er^{3+} ions suggests that the fabrication technology of fibres can be further improved to enhance the efficiency of these lasers.

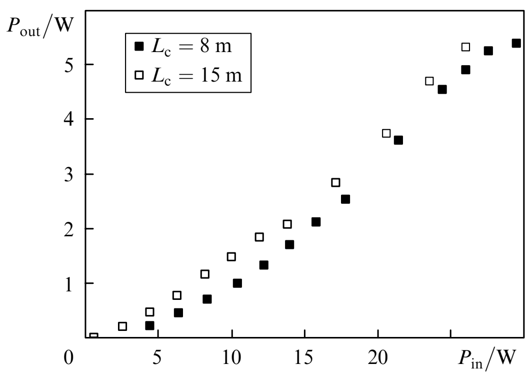

Figure 8. Dependence of the 1608-nm output power on the 975-nm pump power for two different Er–Yb-doped fibre lasers with the resonator lengths $L_c = 8$ and 15 m.

5. Nd-doped fibre lasers emitting at 0.92 and 1.05 μm

Unlike previous papers, we used in this work the MFC fibres to fabricate neodymium lasers emitting at 0.92 and 1.06 μm. This makes it possible not only to increase the pump power coupled to the laser but, due to the use of the active fibre with a circular cross section, also to reduce considerably splicing losses at splices of this fibre with fibres in which FBGs were written, thereby increasing the lasing efficiency. In addition, the use of the MFC fibre allows pumping of the fibre from two sides (Fig. 3) or by turning around pump radiation (Fig. 7). This provides a more homogeneous distribution of the excited Nd^{3+} ions over the laser length, which results in the increase in the optimal length of the laser and allows a greater absorption of the pump power.

We fabricated efficient cw Nd-doped fibre lasers based on two-element first-cladding fibres emitting at 0.92 and 1.06 μm at room temperature. The 805-nm pump radiation from two NewOptics diode modules was coupled from two sides into a passive fibre. The resonator was formed by a highly reflecting FBG written in a fibre, which was spliced to the signal fibre, and by the perpendicular cleave of a single-mode fibre spliced to the signal fibre from the other side.

5.1 Neodymium laser emitting in the range 0.92 – 0.93 μm

The signal fibre of the 0.92-μm laser had a W-index core with the index difference $\Delta n^+ = 5 \times 10^{-3}$ between the core and silica cladding and the index difference $\Delta n^- = 2.5 \times 10^{-3}$ between the depression region and silica cladding (Fig. 9). The diameters of the core and depression region were 6 and 13.5 μm, respectively, the diameter of silica claddings of the signal and passive fibres was 82 μm. The resonator length was 15 m. In this case, the coefficient of absorption from the first cladding at 805 nm amounted to 0.55 dB m^{-1}. An increase in the resonator length resulted in a decrease in the lasing efficiency, whereas the use of the resonator of length smaller than 15 m could lead to the interaction between counterpropagating pump radiations and, hence, to the damage of diode modules because in this case a great part of the pump power is not absorbed in the active fibre of the laser.

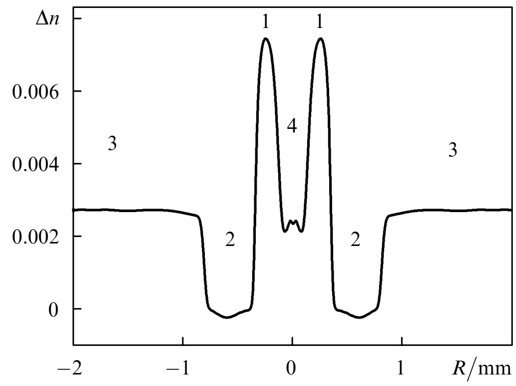

Figure 9. Refractive index profile of an active fibre preform (on the abscissa the radial coordinate of the preform is plotted, on the ordinate – a change in the refractive index): (*1*) core region doped with Nd, Al, and Ge oxides; (*2*) refractive-index depression region doped with fluorine; (*3*) region of pure fused silica; (*4*) undoped core region.

The main difficulty in using a W-index fibre to obtain lasing at 0.92 μm is that along with the efficient suppression of amplification at 1.06 μm it is necessary to preserve the required levels of losses at 0.92 μm, which is achieved by a proper selection of the optimal radius of bending of the laser fibre. To suppress additionally the gain at 1.06 μm, the fibre was coiled over a spool of radius 10 cm.

To increase the lasing efficiency at 930 nm, we performed circular doping of the signal fibre core with neodymium ions. Such a distribution of active ions results in the suppression of the gain per unit length due to a decrease in the overlap integral for the fundamental-field mode and the distribution of active ions. At the same time, the number of neodymium ions per unit length is preserved, so that the absorption coefficient for the pump from the first cladding remains invariable, while the gain per unit length at 0.92 and 1.06 μm decreases. In this case, to suppress lasing at 1.06 μm, a considerably lower level of induced losses per unit length is required, which results in the reduction of the introduced losses at the operating wavelength and allows the use of a longer signal fibre, thereby increasing the absorption coefficient for the pump radiation over the active fibre length.

A similar method of circular doping was used to obtain oscillation at 0.975 μm in a single-mode ytterbium laser pumped through the first cladding [28].

The threshold pump power for the 0.93-μm neodymium laser was 1 W, while the maximum output power achieved 2.2 W. The slope efficiency with respect to the pump power was 22 %. The emission spectrum of the laser and its output parameters are presented in Fig. 10. One can see that no emission is observed at 1.06 μm, which illustrates the efficient gain suppression in this range.

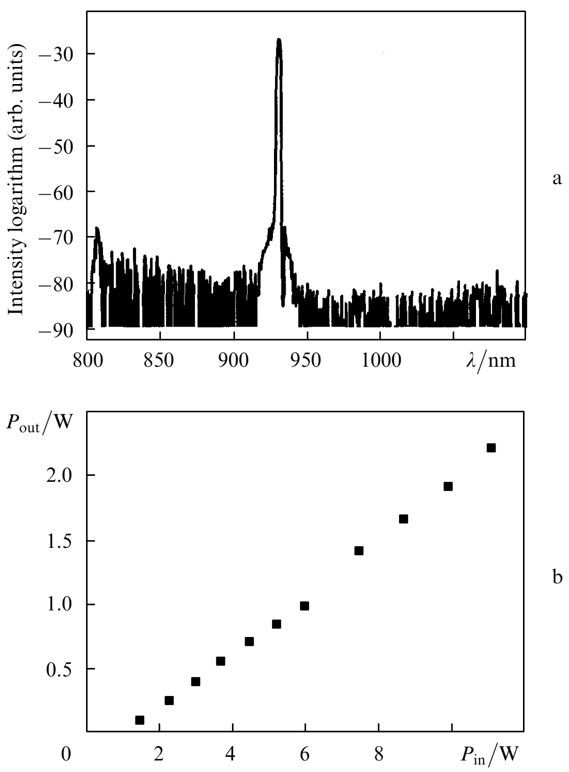

Figure 10. Emission spectrum of the Nd-doped fibre laser (a) and the dependence of the 930-nm output power on the 805-nm pump power (b).

5.2 1.06-μm neodymium laser

To estimate the efficiency of laser diodes with the W-index fibre, we fabricated the 1.06-μm Nd-doped fibre lasers with an approximately step-index fibre. Such fibres do not introduce additional losses at the lasing wavelength. As an active fibre for the laser on the $^4F_{3/2} - ^4I_{11/2}$ transition, we used a two-element first cladding fibre with the following parameters: the refractive index difference for the fibre core and silica cladding was 9.7×10^{-3}, the core diameter was 7 μm, and the diameter of the silica claddings of the passive and active fibres was 80 μm. The fibre length was 21 m and was selected to provide the required absorption of pump radiation (the maximum of the 805-nm absorption band was ~ 1 dB m^{-1}). The highly reflecting FBG had the reflection band at 1.06 μm. The lasing threshold was ~ 0.2 W, and the maximum output power achieved 3.7 W. The slope efficiency of lasing at 1.06 μm with respect to the pump power was 38%. The emission spectra for different pump powers and the output characteristic of the laser are presented in Fig. 11. The efficiency of this laser was higher approximately by a factor of 1.7 than that of the 0.93-μm laser, which probably suggests that additional losses exist at a wavelength of 0.93 μm in the laser based on the W-index fibre and indicates to the possibility of improving lasers of this type.

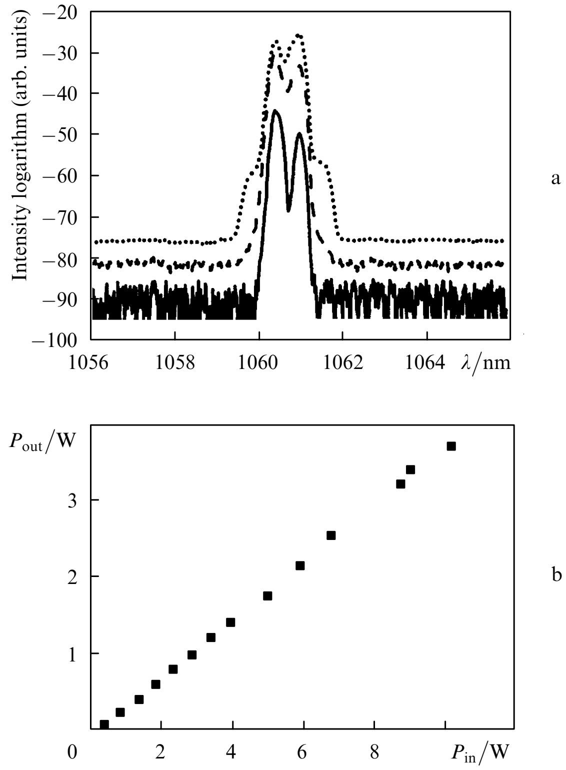

Figure 11. Emission spectra of the Nd-doped fibre laser for different pump powers (a) and the dependence of the 1060-nm output power on the 805-nm pump power (b).

6. Conclusions

We have fabricated and studied single-mode Yb-, Er–Yb-, and Nd-doped fibre lasers based on multi-element first cladding fibres. The use of MFC fibres allows the fabrication of efficient all-fibre lasers pumped simultaneously by a few sources, which is convenient for their applications and makes it possible not only to increase the output power but also to prevent the damage of diode pump sources by the radiation of the fibre laser transmitted through a highly reflecting FBG. The results obtained in the paper show that MFC fibres are very promising for applications in fibre optics.

Acknowledgements. The authors thank O.I. Medvedkov for fabricating FBGs for lasers and A.E. Rakitin for his help in conducting experiments. This work was partially supported by the grant of the President of the Russian Federation No. NSh-962.2003.2.

References

1. Jeong H, Sahu J.K., Baek S., et al. *Proc. CLEO'2004* (Baltimore, MD, USA, 2004) CMS1.
2. Liu C.-H., Galvanauskas A., Ehlers B., et al. *Proc. CLEO'2004* (Baltimore, MD, USA, 2004) CMS2.
3. Platonov N.S., Gapontsev D.V., Shumilin V. *Proc. CLEO'2002* (Long Beach, CA, 2002) CPDC3.
4. Jeong Y., Sahu J.K., Williams R.B., et al. *Electron. Lett.*, **39**, 977 (2003).
5. Limpert J., Liem A., Zellmer H., Tunnerman A. *Electron. Lett.*, **39**, 645 (2003).
6. Jeong Y., Sahu J.K., Payne D.N., Nilsson J. *Proc. ASSP'2004* (Santa Fe, New Mexico, 2004).
7. Norman S., Zervas M., Jeong Y., et al. *Photonics West'2004* (San Jose, CA, 2004).
8. Fomin V., Sivov B. *II International Symposium on High-Power Fiber Lasers and Their Applications* (St.-Petersburg, Russia, 2003) 2.1.
9. Sahu J.K., Jeong Y., Richardson D.J., Nilsson J. *Opt. Commun.*, **227**, 159 (2003).
10. Zeller P., Peuser P. *Opt. Lett.*, **25**, 34 (2000).
11. Dawson J.W., Drobshoff A., Liao Z., et al. *Proc. SPIE Int. Opt. Eng.*, **4974**, 75 (2003).
12. Bufetov I.A., Dudin V.V., Shubin V.V., et al. *Kvantovaya Elektron.*, **33**, 1035 (2003) [*Quantum Electron.*, **33**, 1035 (2003)].
13. Soderlund M.J., Tammela S.K.T. *Proc. OFC'2004* (Los Angeles, CA, USA, 2004) FJ4.
14. Soh D.B.S., Yoo S.W., Nilsson J., et al. *IEEE J. Quantum Electron.*, **9**, 1275 (2004).
15. Kawakami S., Nishida S. *IEEE J. Quantum Electron.*, **4**, 130 (1975).
16. Monerie M. *IEEE Transactions on Microwave Theory and Techniques*, **4**, 381 (1982).
17. Unger H.-G. *Planar Optical Waveguides and Fibres* (Oxford: Clarendon Press, 1977; Moscow: Mir, 1980).
18. Cohen L.G., Marcuse D., Mammel W.L. *IEEE J. Quantum Electron.*, **18**, 1467 (1982).
19. Arbore M.A., Zhou Y., Keaton G., Kane T. *Proc. ECOC'2002* (Copenhagen, Denmark, 2002) 2.2.2.
20. Ripin D.J., Goldberg L. *Electron. Lett.*, **31**, 2204 (1995).
21. Li C., Song J., Kim N.S., Ueda Kenichi. *Proc. SPIE Int. Opt. Eng.*, **3862**, 246 (1999).
22. Hakimi F., Hakimi H. *CLEO'2001* (Baltimore, MD, USA, 2001) CTUD2.
23. Ou P., Yan P., Gong M.L., et al. *Electron. Lett.*, **40**, 7 (2004).
24. Grudinin A.B., Turner P.W., Codemard C., et al. *Proc. ECOC'2002* (Copenhagen, Denmark, 2002) PD1.6.
25. Doya V. *Opt. Fiber Technol.*, **6**, 324 (2001).
26. Mel'kumov M.A., Bufetov I.A., Kravtsov K.S., et al. *Kvantovaya Elektron.*, **34**, 843 (2004) [*Quantum Electron.*, **34**, 843 (2004)].
27. Dianov E.M., Belov A.V., Bufetov I.A., et al. *Kvantovaya Elektron.*, **24**, 3 (1997) [*Quantum Electron.*, **27**, 1 (1997)].
28. Nilsson J., Minelly J.D., Paschotta A.C., et al. *Opt. Lett.*, **23**, 355 (1998).