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Efficient 0.9-μm neodymium-doped single-mode fibre laser

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***Abstract*.** **An efficient cw single-mode double-clad Nd^{3+}-doped fibre laser is developed which operates at room temperature in a quasi-three level scheme on the 925-nm $^4F_{3/2} - {}^4I_{9/2}$ transition upon diode pump at 805 nm. The gain in the laser resonator at 1.06 μm is strongly suppressed due to a proper choice of the refractive index profile in the fibre core. The laser output power above 0.5 W is obtained with the slope efficiency exceeding 35 %.**

***Keywords*:** *fibre laser, double-clad fibre, Bragg grating.*

The designs of double-clad neodymium-doped fibre lasers emitting at the 1.06-μm $^4F_{3/2} - {}^4I_{11/2}$ transition are well known (see, for example, Ref. [1]). However, to obtain lasing at the 0.9-μm $^4F_{3/2} - {}^4I_{9/2}$ transition is more difficult because in this case the laser operates in a quasi-three level scheme and the gain in the four-level scheme at the $^4F_{3/2} - {}^4I_{11/2}$ transition will be always greater than that at the $^4F_{3/2} - {}^4I_{9/2}$ transition (the cross sections for these transitions can be considered approximately identical; see, for example, Ref. [2]).

The development of such a fibre laser pumped through its cladding opens up the way for obtaining single-transverse mode emission at 0.92 μm with a power comparable to the output power of ytterbium-doped double-clad fibre lasers (from units to hundreds of watts). This will make it possible, first, to create a high-power source of blue light by frequency doubling, second, to use the $\sim$ 0.92-μm radiation for pumping ytterbium-doped fibre lasers and amplifiers at 0.98 μm and, third, using Raman fibre lasers as frequency converters, to obtain emission of approximately the same power at any wavelength above 0.9 μm in the transparency window of silica fibres.

To develop such a neodymium-doped fibre laser, it is necessary to introduce somehow additional losses to its resonator at a wavelength of 1.06 μm. Pumping directly into the fibre core can produce lasing at the $^4F_{3/2} - {}^4I_{9/2}$ transition due to the difference in the reflection coefficients of the resonator mirrors at the wavelengths 0.92 and 1.06 μm [3, 4]. The maximum power obtained at present in such a scheme was 43 mW [5]. Compared to pumping into the fibre core, the use of a double-clad fibre (and, hence, the use of cheaper multimode laser diodes as pump sources) reduces, as a rule, the pump intensity in the core by several orders of magnitude at the same power, which hinders the suppression of the gain at 1.06 μm.

Until recently, the output power of the order of a few watts was obtained at this transition only in YAG and YVO_4 crystal matrices [6]. A fibre laser on the $^4F_{3/2} - {}^4I_{9/2}$ transition pumped through the cladding was realised only by cooling the fibre to liquid nitrogen temperature, thereby passing to the four-level lasing scheme [7].

In this paper, we obtained efficient high-power lasing under normal conditions in a quasi-three level scheme at the $^4F_{3/2} - {}^4I_{9/2}$ transition in neodymium ions in a double-clad Nd-doped silica fibre. To provide the best absorption of pump radiation and low optical losses, Nd_2O_3 (mass concentration 1 %), Al_2O_3 (molar concentration 1 %), and GeO_2 (molar concentration 1 %) were introduced into the fibre core.

To ensure the required optical losses in the 1.06-μm band for supressing lasing in this region, the index profile of the fibre was chosen in the form shown in Fig. 1. It is known [8 – 11] that the fundamental mode in fibres with such an index profile (W-fibres) has a finite cut-off wavelength (unlike fibres with a step index profile). To reduce the refractive index in the depression region, fluorine was doped into a fibre preform and the fibre cladding was made of pure silica glass. The sizes of the fibre core and the depression region were chosen so that the fundamental-mode cut-off wavelength lied between 925 and 1060 nm, resulting in substantial radiation leak losses at 1.06 μm. Note that a similar index profile was used in Ref. [12], which provided the suppression of the gain at 1530 nm in an erbium-doped fibre amplifier for the operation in the gain S band (between 1480 and 1520 nm).

The scheme of the experimental setup is shown in Fig. 2. An active element is a double-clad Nd-doped fibre with a single-mode core. The cross section of the external (first) silica cladding of the fibre had the shape of a square (as in

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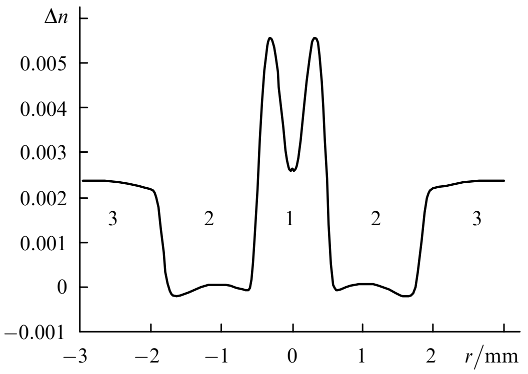

Figure 1. Refractive index profile of an active fibre preform: (1) core doped with Nd, Al, and Ge oxides; (2) refractive-index depression region doped with F; (3) inner cladding made of pure silica.

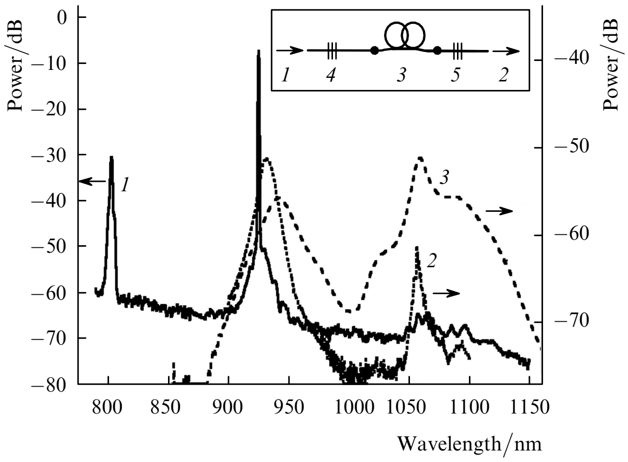

Figure 2. Emission spectrum of a neodymium-doped fibre laser (*1*). The 805-nm peak is the unabsorbed pump radiation, the 925-nm peak is laser emission, and the 1060-nm peak is the residual luminescence emission. For comparison are also shown the luminescence spectrum (*2*) at the output of the fibre laser pumped below the threshold and the luminescence spectrum (*3*) of the fibre laser without the refractive-index depression region. The inset shows the scheme of the laser: (*1*) 805-nm pump radiation; (*2*) 925-nm output radiation; (*3*) active fibre; (*4*) Bragg grating with the reflectivity $R \approx 100\,\%$; (*5*) output Bragg grating with $R = 20\,\%$.

Ref. [1]) with a side of 104 μm. The laser resonator was formed by a pair of Bragg gratings with the maximum reflectivity at 925 nm and the spectral width of ~ 1 nm, which were written in the core of a single-mode photosensitive fibre. The pieces of fibres with Bragg gratings were spliced to both ends of the active fibre.

The refractive index of the polymer coating of fibres was lower than that of silica, so that the first cladding of fibres was itself a multimode fibre with a numerical aperture of 0.4. Pumping at 805 nm was performed by a multimode laser diode with a fibre coupling out of radiation (the fibre core diameter was 220 μm and the numerical apertures was 0.22). The pump radiation was coupled to the first cladding of the fibre with the help of an objective from the side of a highly reflecting Bragg grating.

The spectrum and power of emission were measured at the output of the fibre laser. When the pump radiation power was below the lasing threshold, the luminescence spectrum of Nd^{3+} ions in the fibre core [curve (*2*) in Fig. 2] was recorded at the output of the fibre laser (inset in Fig. 2). For comparison, Fig. 2 also shows the luminescence spectrum [curve (*3*)] of Nd^{3+} ions in another fibre with approximately the same composition of the core in the same scheme but without the refractive-index depression region (the parameters of this fibre are presented in Ref. [1]). Both the spectra are normalised to the same value at the maximum. The maximum of luminescence in the fibre with the refractive-index depression region (Fig. 1) was observed at 930 nm, while the intensity of the 1060-nm band was approximately an order of magnitude lower. In the fibre without the refractive-index depression region, the ratio of the intensities of the 930-nm and 1060-nm bands was inverse, which demonstrates the presence of additional optical losses at 1060 nm.

As the pump power was increased, lasing at a wavelength of 925 nm appeared. The emission spectrum recorded in this case is shown in Fig. 2 [curve (*1*)]. Emission at 1060 nm is very weak, and only weak unabsorbed part of the pump radiation is observed at 805 nm in the spectrum.

The optimal length of the fibre (corresponding to the maximum lasing efficiency under our experimental conditions) was 5.4 m. In this case, the absorbed pump power at the lasing threshold was ~ 500 mW and the slope efficiency was 36 %. Figure 3 shows the dependence of the laser output power on the pump power. The maximum output power of the fibre laser was 0.51 W at the lasing efficiency equal to 25 % (with respect to the absorbed pump power).

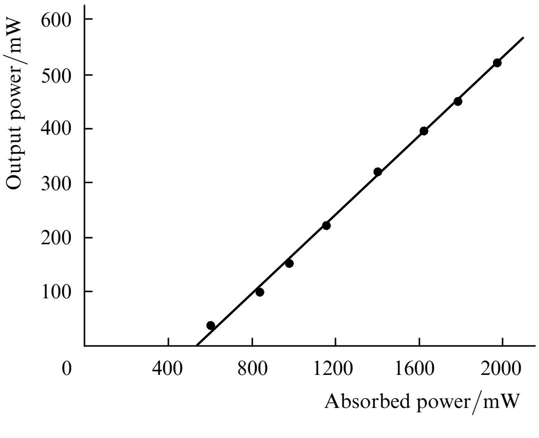

Figure 3. Dependence of the 925-nm laser output power on the absorbed 805-nm pump power (the length of the active fibre region is 5.4 m).

Thus, we have obtained efficient generation in a double-clad Nd-doped fibre laser at 0.9 μm at room temperature. The gain at 1.06 μm was suppressed by using the W-shaped index profile of the fibre core. The achieved lasing efficiency of 25 % can be increased by pumping the laser by more intense sources and decreasing correspondingly the cross section of the first cladding of the fibre. By using a fibre laser of this type and higher-power pump sources, which are available at present, the output powers from 10 to 20 W can be achieved. In addition, the active fibres used in the paper can be employed in neodymium-doped fibre amplifiers operating at 0.9 μm, which the authors plan to report in near future.

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