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Neodymium-doped graded-index single-crystal fibre lasers

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Abstract. **The efficient technology is developed for growing high-quality doped single-crystal fibres by the mini-pedestal method with laser heating. The technology can be used to fabricate high-quality doped single-crystal fibres with a controllable radial gradient of the refractive index. The refractive-index profile in single-crystal fibres is studied experimentally. The efficient operation of a Nd^{3+} : YAG single-crystal fibre laser in the waveguide regime was demonstrated upon longitudinal pumping by a laser diode.**

Keywords: *single-crystal fibre, Nd^{3+} : YAG, solid-state laser, fibre laser.*

1. Introduction

At present various laser radiation sources are required for fibreoptic communications. However, these sources (laser diodes, erbium-doped fibre lasers and amplifiers, Raman amplifiers, etc.) should satisfy some requirements concerning the radiation frequency stability, thermal characteristics, mechanical strength, and ionising radiation resistance.

Single-crystal fibres combine all the positive qualities of single crystals (high strength and high quantum yield of luminescence, a variety of activators and laser transitions in rare-earth ions, etc.) with the specific properties of optical fibres. Although interest in the fabrication and applications of doped single-crystal fibres in laser technologies aroused long ago [1 – 3], due to the difficulty of fabrication of fibres and a low lasing efficiency in the waveguide scheme, only few experiments were performed with these fibres.

The original setup developed by using the mini-pedestal method with laser heating [4] makes it possible to grow high-quality crystal fibres and to obtain efficient lasing in the region near 1 μm [5].

In this paper, we describe our further experiments on growing single-crystal fibres doped with neodymium ions and study the lasing characteristics of Nd^{3+} : YAG fibres longitudinally pumped by semiconductor lasers. The aim of our paper was to investigate the influence of the growth technology on the optical properties and lasing characteristics of crystal fibres for increasing the efficiency of fibre lasers.

2. Growing of single-crystal fibres

Crystal fibres used in experiments were grown by the mini-pedestal method with laser heating [1, 2] in an oxidising atmosphere. In this method, the end of a specially prepared cylindrical single-crystal or polycrystalline oxide preform oriented vertically is exposed to axially symmetrically focused radiation from a CO_2 laser, which melts the preform material by forming a drop of the melt hold by surface tension forces. A seed crystal oriented in the required crystallographic direction is inserted into this region. The seed crystal is brought into contact with the melt and then is being drawn at the specified velocity from the heated zone. On the end of the seed a nearly cylindrical single crystal, the so-called single-crystal fibre, is formed (Fig. 1). During the drawing of the growing crystal, a preform is fed into the heated zone to compensate for the consumption of the material carried away from the melt by the grown fibre.

An important feature of our setup [5, 6] (Fig. 2) is the use of a focusing unit – a special optical element producing the circular power distribution over the laser-beam cross section (Fig. 3). Unlike similar setups described in the foreign literature, which use complicated optical systems of the ‘cone in cone’ type to produce a radiation beam in the

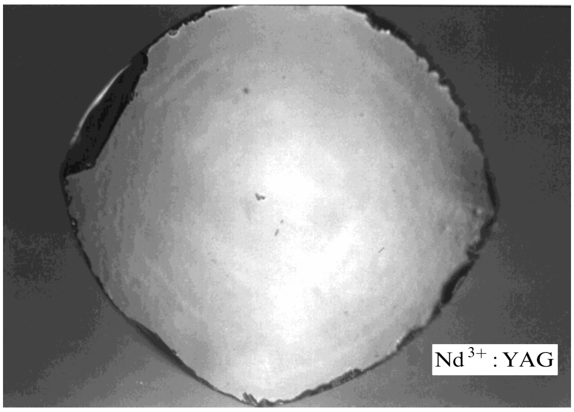

Figure 1. Photograph of the end of a Nd^{3+} : YAG single-crystal fibre of diameter 450 μm grown along the [100] crystallographic axis.

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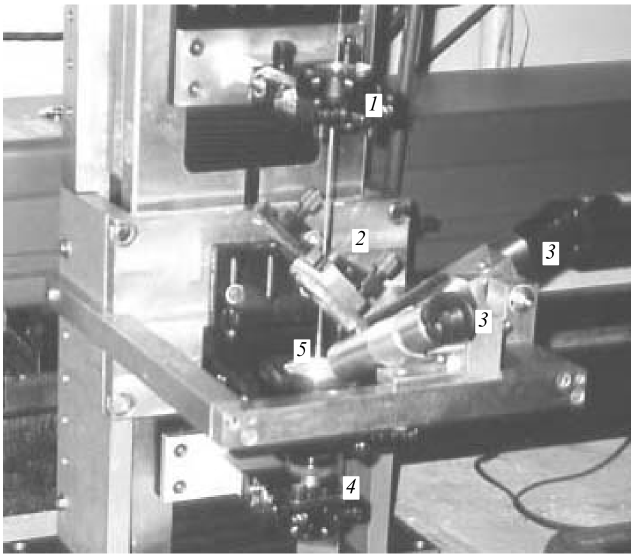

Figure 2. Setup for growing single-crystal fibres: (*1*) fibre drawing unit; (*2*) focusing unit; (*3*) microscopes to control the growth process; (*4*) preform feeding unit; (*5*) melting zone.

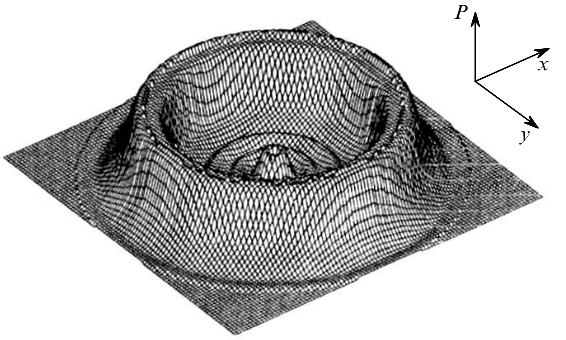

Figure 3. Circular distribution of the laser radiation power P in the focal region of a diffraction reflection transformer (focusing unit) [9].

form of a hollow cylinder, our focusing unit is low-cost, it can be easily adjusted, and its efficiency is almost independent of the mode composition of radiation.

We used crystal matrices of yttrium – aluminium garnet ($Y_3Al_3O_{12}$) and yttrium oxide (Y_2O_3) doped with neodymium ions and having well-known mechanical and luminescence properties.

3. Study of optical and lasing properties

Crystal fibres of length from 10 to 100 mm and diameter 450 – 700 μm were grown from polycrystalline (Y_2O_3 crystals) and single-crystal (YAG crystals) preforms. We fabricated yttrium oxide single-crystal fibres with different concentrations of Nd^{3+} ions (1.0×10^{20}, 4.5×10^{20}, 9.0×10^{20}, 18.0×10^{20} and 36.0×10^{20} cm^{-3}) and Nd^{3+} : YAG fibres with the average concentration of neodymium ions ~1 % (~1.5×10^{20} cm^{-3}). Fibres of both types had a high optical quality (they did not contain scattering centres, gas bubbles, and inclusions); however, yttrium oxide crystal fibres cracked within several days after their growing. Therefore, we studied only the luminescence properties of yttrium oxide fibres, while for Nd^{3+} : YAG fibres both optical and lasing properties were studied. The cracking of Y_2O_3 single-crystal fibres was caused, as mentioned earlier, by the adsorption of water on the crystal surface and is a unique property of this crystal matrix.

Luminescence properties were studied at room temperature upon excitation by a semiconductor laser diode in the region 808 – 810 nm. The spectral resolution was 0.26 nm. The luminescence lifetime was measured upon excitation by the 10-ns second-harmonic pulses from a *Q*-switched Nd^{3+} : YAG laser.

The luminescence characteristics of Nd^{3+} : YAG fibres completely coincided with the data reported in the literature. The luminescence spectra of Nd^{3+} : YAG fibres were in agreement with the known spectra, whereas the luminescence lifetime decreased with increasing the concentration of Nd^{3+} ions (Table 1) faster than in [7]. It can be explained by the inhomogeneous distribution of impurity centres over the fibre volume (as in the case of Nd^{3+} : YAG fibres) resulting in the increase in the effective impurity concentration compared to its average value.

Table 1. Dependence of the concentration of Nd^{3+} ions on the luminescence lifetime of these ions in Y_2O_3 single-crystal fibres.

Lifetime/μs	Nd^{3+} ion concentration/cm^{-3}
280	1×10^{19}
38	4.5×10^{20}
16	9×10^{20}
5	18×10^{20}
1	3.6×10^{21}

The Nd^{3+} : YAG fibres studied in the paper were grown at different preform heating powers and different fibre drawing velocities (from 10 to 150 mm h^{-1}). The fabricated crystal fibres were cut into pieces of length 5 – 35 mm, in which the distribution of impurity ions over the fibre cross section and the refractive index profile were studied. The samples were also used as active elements to study lasing.

The homogeneity of the distribution of neodymium ions over the volume of crystal fibres was studied with an electron microscope. The inhomogeneous distribution of impurity neodymium ions over the cross section of crystal fibres observed earlier in [4, 5] was also found in some

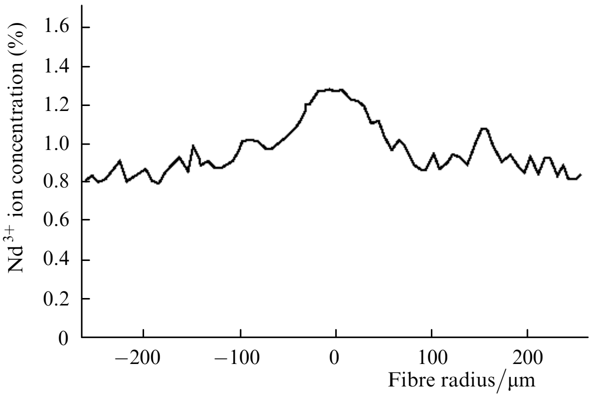

Figure 4. Distribution of the concentration of Nd^{3+} ions over the cross section of Nd^{3+} : YAG fibre.

samples under study (Fig. 4). The maximum concentration of neodymium ions was observed in the central part of a crystal fibre and was 1.3 %, while the concentration at the periphery was 0.8 %.

The refractive-index profile in fibres was studied by the near-field method, which gave us qualitative but quite clear results. We found that the refractive index of crystal fibres with the inhomogeneous distribution of neodymium ions over the fibre cross section was also inhomogeneous (Fig. 5). Quantitative variations in the refractive index were studied by measuring the numerical aperture of a crystal fibre using an incandescent lamp as a probe source. We found that the numerical aperture of the fibre was NA $\approx 0.028 \pm 0.005$, i.e., the refractive index at the fibre centre was higher by 0.0002 than its value at the fibre periphery, which provided the waveguide propagation of light in this fibre.

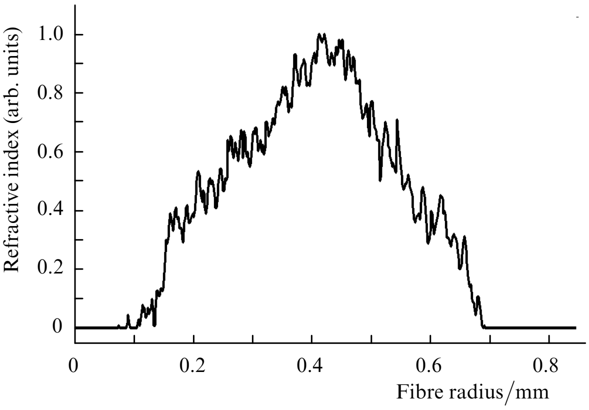

Figure 5. Refractive-index profile (probe beam intensity) in a Nd^{3+} : YAG fibre measured by the near-field method.

It was assumed earlier [5] that the inhomogeneous distribution of impurity neodymium ions over the cross section of a crystal fibre is inherent in the mini-pedestal growth method with laser heating, whereas other methods (for example, the method of fibre drawing though a die [8]) give the homogeneous impurity distribution. However, it was shown in our experiments that the type of distribution of impurities over the cross section of a crystal fibre depends on the growing conditions. Thus, by changing the heating power supplied to the growth region and the fibre drawing velocity, both homogeneous and inhomogeneous distributions of the impurity concentration and, hence, different refractive-index profiles can be obtained. The mechanism of this process will be studied in the future experiments.

Lasing was studied in crystal Nd^{3+} : YAG fibres of length from 5 to 35 mm with the inhomogeneous refractive-index profile. The ends of active fibres had no AR coatings. Two types of resonators with external mirrors, spherical or hemispherical, were used in experiments (Fig. 6). One of the mirrors was highly reflecting (HR) with the reflectance of 99.8 % at the lasing wavelength 1.06 µm and the transmittance of 90 % at the pump wavelength 808 nm. The reflectance of the output mirror of the resonator at 1.06 µm was 98 %. The pump radiation was focused with a thin lens through the HR mirror on the end of a crystal fibre. However, this simple scheme could not provide the focal spot diameter on the end of an active element smaller than 300 µm because the source size was 600 µm (a 4-W laser diode with a fibre pigtail of diameter 600 µm). In the case of a concave HR mirror, the minimal diameter of the focal spot was 350 µm because the substrate of the HR mirror played the role of a scattering lens.

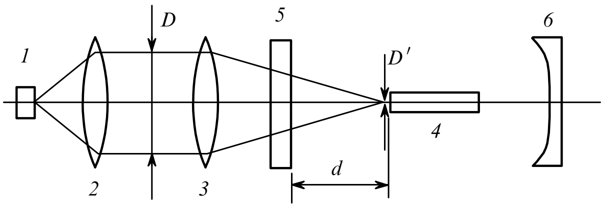

Figure 6. 6. Scheme of the resonator with Nd^{3+} : YAG fibre active elements: (*1*) pump source (laser diode); (*2*, *3*) lenses; (*4*) crystal fibre (diameter 450–600 µm, length 5–36 mm); (*5*) plane or concave rear mirror (reflectance $R = 99.8\,\%$, radius of curvature $r = 50$ mm); (*6*) concave output mirror ($R = 98\,\%$, $r = 50$ mm); $D = 16 - 20$ mm is the pump beam diameter; $D' = 300 - 400$ µm is the pump spot diameter; $d = 1 - 3$ mm.

The resonator was adjusted in such a way as to prevent lasing at usual resonator modes because the resonator length exceeded the maximum length of a stable resonator, the ends of the fibre being in the focus of the resonator mirrors.

The pump radiation incident on the active element at an angle of $\sim 20°$ experienced total internal reflection from the side surface and filled the total volume of the fibre. The laser spot size on the end of the active element was ~ 100 µm (Fig. 7) for 'long' (more than 10 mm) active fibres and 300–350 µm for 'short' (5 mm) fibres.

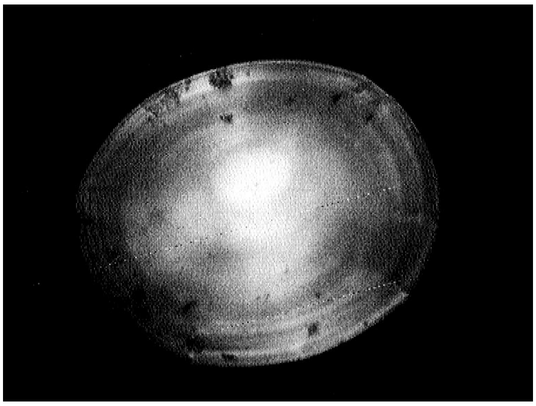

Figure 7. Photography of the end of a Nd^{3+} : YAG fibre of diameter 500 µm obtained during lasing.

The output power of the Nd^{3+} : YAG fibre laser with a hemispherical resonator as a function of the pump power is presented in Fig. 8 for the fibre length of 28 mm. Note that the hemispherical scheme prove to be less sensitive both to the angular misalignment of the mirrors and a change in the resonator length. For short active fibres of length 5–6 mm in both schemes, we also studied the laser action in a standard regime when the geometric parameters of the resonator were in the stable region. In this case, the efficiency and output power of the laser were approximately an order of magnitude lower than in the waveguide scheme and approximately corresponded to the results obtained for non-waveguide (with a constant refractive index) fibres. As

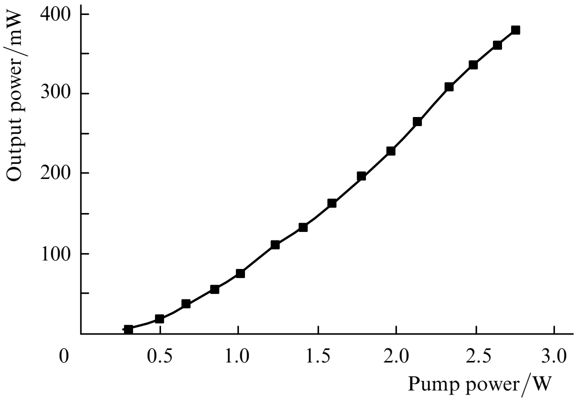

Figure 8. Lasing characteristic of a Nd^{3+} : YAG single-crystal fibre of length 28 mm and diameter 500 μm placed in a hemispherical resonator.

the resonator length was increased, lasing in non-waveguide fibres disappeared unlike fibres with the radial gradient of the refractive index.

The results of lasing experiments confirm the fact that the waveguide propagation regime of radiation in a crystal fibre takes place in the absence of total internal reflection from the side surface of the fibre. This regime appears due to the radial gradient of the refractive index, which in turn is determined by gradient of concentration of Nd^{3+} ions. Thus, it is possible to avoid considerable losses caused by imperfections of the side surface of the single-crystal fibre.

Because the active-medium volume is small, the absorbed pump power density can achieve rather high values. Thus, the maximum absorbed power density in our experiments was 500 W cm^{-3}. By using the interference method, we estimated the temperature to which the active element is heated in the case of poor heat removal. The sample was mounted in a plastic holder with the heat conductivity 0.2 W m^{-1} K^{-1}, and the temperature of the active element was estimated by the number of 'accumulated' interference fringes. In the case of poor heat removal, the active fibre element of length 6 mm and diameter 500 μm absorbing ~0.4 W of pump power was heated up to ~200 °C during two minutes of pumping. Therefore, it is necessary under these conditions to provide the efficient heat removal from the active element.

4. Conclusions

We have developed the efficient technology for growing high-quality doped single-crystal fibres with a controllable radial gradient of the refractive index. The efficient lasing in the waveguide regime has been demonstrated in Nd^{3+} : YAG fibres longitudinally pumped by a semiconductor laser diode. It has been shown that the influence of the imperfections of the side surface of a fibre is compensated to a great extent by the waveguide propagation regime of radiation in the active fibre due to the radial gradient of the refractive index. The fabrication of monolithic active fibre elements with mirrors deposited on the fibre ends will allow the development of new devices for fibreoptic technologies.

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