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Ceramic planar waveguide structures for amplifiers and lasers

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Abstract. **Ceramic and crystalline weakly guiding optical fibres with the core–cladding refractive index difference of 10^{-2}–10^{-4} are fabricated by a hot pressing method. The waveguides with one or several cores for operation in the spectral range 0.2–5 μm are produced. The waveguides are based on CaF_2, SrF_2, and BaF_2 ceramics and crystals and their solid solutions doped with trivalent Pr, Nd, Tb, Dy, Yb, Ho, Er, and Tm ions, as well as on LiF ceramics and crystals with colour centres. The first results of investigation of the lasing properties of ceramic SrF_2:NdF waveguides under diode pumping are presented, and the prospects of further investigation are discussed.**

Keywords: *ceramic and crystalline planar optical waveguides, hot pressuring.*

1. Introduction

The appearance of high-power laser diodes for pumping laser media stimulated interest in the development and investigation of new types of planar optical waveguides [1–4]. Planar waveguides (PWs) [5], which are used as active laser media, have some advantages compared to bulk materials. These advantages are, in particular, a large light–matter interaction length and preservation of linear polarisation of laser radiation. Planar waveguides can be created using various materials (semiconductors, crystals, glasses) [6–8], as well as using various technological methods. For laser and nonlinear optical applications, PWs must have a wide transparency range and a high laser or nonlinear gain coefficient. One also must take into account the pump path length, the transverse size of the waveguiding core, the core–cladding refractive index difference, the mode composition of radiation, the optical losses, and the dispersion characteristics.

In this paper, we report on the development of methods for fabricating planar (Fig. 1) ceramic and crystalline weakly guiding [5] waveguides with the core–cladding refractive index difference $\Delta n = n_1 - n_2 = 10^{-2}$–$10^{-4}$. For operation in the spectral range 0.2–5 μm, we designed PWs with one or several cores based on CaF_2, SrF_2, BaF_2 fluoride ceramics and crystals and their solid solutions. Ceramic materials have better microhardness and crack resistance than corresponding crystals, as well as good thermophysical properties. Ceramics and crystals for PWs were doped with trivalent Pr, Nd, Tb, Dy, Yb, Ho, Er, and Tm ions. In addition, we developed PWs based on LiF crystals with F^{2-} and F^{2+} colour centres. The main advantages of these PWs compared to glass waveguides are high gains and the possibility of formation of a large number of simultaneously excited active channels with coherent and incoherent summation of the fields of excited modes in one PW. We also present the first results on lasing in PWs under laser diode pumping and consider the prospects of further investigations in this field.

2. Experimental methods

To fabricate PWs with a step-wise refractive index distribution (Fig. 1), we used materials with the closest thermal expansion coefficients. The PW dimensions were varied in a wide range. The PW length (along the x axis) reached 100 mm. The thickness (along the z axis) of plates forming the core was varied within approximately 0.1–0.5 mm, and the width (along the y axis) of plates was 0.1–20 mm. To develop a PW, a plate for the waveguide core, which was made of fluoride ceramics or crystal and polished from two sides, was attached between two polished plates of cladding. This three-layer structure was uniaxially pressed at the temperature of plasticity of the materials. The multilayer block was finally polished perpendicular to the layers. PWs with several cores were made using several core plates of identical thickness, which were placed between cladding plates and hot pressed.

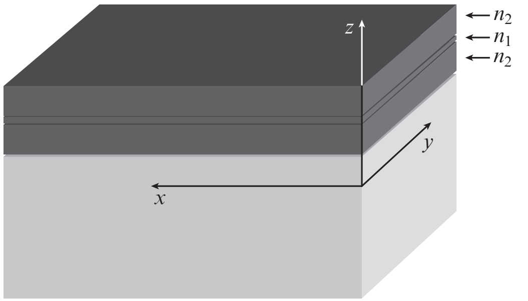

Figure 1. Structure of a planar waveguide.

An image of a facet of a waveguide structure obtained by hot pressing of a crystalline (SrF_2) and a ceramic (SrF_2:NdF_3) plates is presented in Fig. 2a. A similar image of a waveguide structure with a cladding of crystalline (SrF_2) plates and a core of a ceramic (SrF_2:NdF_3) plate is shown in Fig. 2b. Both photographs demonstrate a good quality of the interface

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between the core and cladding, which points to insignificant variations in the transverse size of the PWs. It should be noted that insufficient quality of the interface leads to transformation of a PW to an irregular waveguide [5], and, as a result, to additional optical losses and probable variations in the radiation polarisation. Such effects can be also caused by variations in the difference $\Delta n = n_1 - n_2$ along the waveguide [9]. (Variations in the core size were observed, in particular, when fabricating a crystalline thin-film waveguide by liquid-phase epitaxy [8].)

To obtain a difference between the refractive indices n_1 and n_2 in our PWs, we used two methods. The first method consists in the choice of different crystals for the core and cladding, for example, LiF and CaF_2. In this case, at a relatively large difference Δn, we also have a rather large difference in the thermal expansion coefficients of the core and cladding, which can lead to unwanted additional stresses (up to breakdown) in the PW during heating in the process of hot pressing. The second, more preferable method is to change the refractive index by using different dopants in the core and cladding (Fig. 2). In this case, the crystals composing a waveguide have the same structure and, hence, close thermal expansion coefficients (neglecting insignificant amounts of impurities). Moreover, this approach allows one to continuously change the difference $n_1 - n_2$ up to very small values, which is important for weakly guiding PWs.

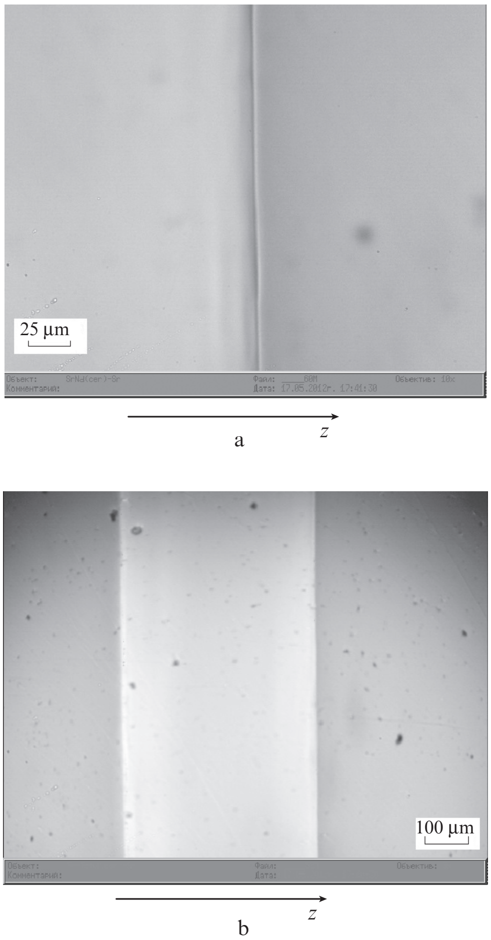

Figure 2. Microscope images of the facets of a waveguide structure obtained by hot pressing of a crystalline SF_2 plate and a ceramic $SrF_2:NdF_3$ plate (a) and of a waveguide structure consisting of a crystalline SrF_2 cladding and a ceramic $SrF_2:NdF_3$ core (b).

Measuring the numerical aperture (NA) at the PW exit, we estimated the difference Δn in a crystalline PW based on $CaF_2-CaF_2:Nd^{3+}-CaF_2$. The concentration of NdF_3 in this case was 0.5 mol %. A beam of a single-mode He–Ne laser (633 nm) was focused into the PW core by a short-focus lens with a large NA. The divergence of the transformed non-concentric beam emitted from the waveguide was measured in two orthogonal directions (z, x) in the far-field zone. Taking into account that $n_1 = 1.4325$ [10], we obtained NA = 0.028. The difference $\Delta n = 2.7\times10^{-4}$ was determined by the formula $\mathrm{NA} = (2n_1\Delta n)^{1/2}$.

3. Laser experiments

We present the results achieved with PWs based on SrF_2 ceramics. The $Nd^{3+}:SrF_2$ crystals and ceramics were developed at the A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, and were found to be promising as materials for diode-pumped lasers [11, 12]. For laser experiments, we chose a PW 15 mm long with a ceramic $SrF_2:NdF_3$ core (NdF_3 concentration 0.5 mol %, thickness 0.2 mm, width 7 mm) and a crystalline SrF_2 cladding. We used input optics and a two-mirror cavity optimised for pumping the crystals [12]. The pump laser diode (LD) was coupled with a multimode fibre with a core diameter of 0.12 mm. The LD beam from the fibre (wavelength 795 nm, pulse duration 3 ms, pulse repetition rate 10 Hz) was focused by a spherical lens ($f = 8-12$ mm) and coupled into the PW through a dichroic plane mirror. The concave (curvature radius 50 mm) output mirror had a reflection coefficient of 95%; the cavity length was ~35 mm. Note that, since the fluorescence decay time of Nd ions in $SrF_2:NdF_3$ is ~3 ms, pumping had a steady-state character.

When a focused pump beam with an NA considerably higher than the NA of the waveguide is coupled into the PW, a considerable portion of the pump power is emitted through the side surface of the PW due to violation of the total internal reflection condition on the core–cladding interface. This circumstance does not allow one to achieve the maximum possible slope efficiency of the laser. Due to the waveguide nature of the PW, the laser beam was non-concentric. The

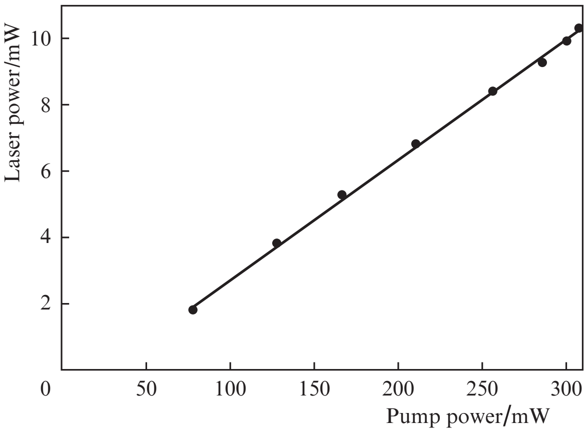

Figure 3. Dependence of the output power of a laser based on an active planar waveguide with a ceramic $SrF_2:NdF_3$ (0.5 mol %) core and a crystalline SrF_2 cladding on the diode pump power.

spectrum of the waveguide laser with the 1037-nm line completely corresponded to the spectra of diode-pumped lasers based on $Nd^{3+}:SrF_2$ crystals and ceramics. The dependence of the PW laser output power on the incident pump power is shown in Fig. 3. The pump power spent to the PW excitation is considerably lower than the measured pump power due to the waveguide losses and the absorption of pump radiation in the active medium. The waveguide laser slope efficiency of 4% measured with a 95% output mirror is considerably lower than 37% obtained for the crystal in [12]. To achieve a higher efficiency, it is necessary, in particular, to match the numerical apertures of the pump beam and PW. This can be done without lens systems, using instead of a multimode fibre and a lens only a waveguide with a small NA.

4. Conclusions

The reported results allow us, after a corresponding optimisation of the optical scheme, to expect successful application of the described planar waveguides in lasers and amplifiers. One of the considered topical problems is the study of several simultaneously excited active channels in PWs with one or several cores. In particular, in the studied PW with a core 7 mm wide (along the x axis) and 0.2 mm thick (along the y axis), one can expect excitation of more than ten active channels in the longitudinal and transverse directions. Each channel corresponds to a group of excited linearly polarised modes with possible intermode energy conversion. The degree of coherence and the total output energy of a PW in this case depend on several factors. In contrast to multichannel waveguide devices, this scheme allows direct excitation of spatially spaced channels by several LDs without using multiplexers (directional waveguide couplers) and control of linear polarisation in each fibre, which considerably simplifies the problem. The large width of the core also makes it possible to excite a PW by an LD array or a singe LD with the use of cylindrical optics.

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