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Planar fluoride waveguides for amplifiers and lasers

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Abstract. **We have produced planar optical waveguides having a crystalline $CaF_2-YF_3-NdF_3$ mixed yttrofluorite core and two reflective claddings in order to improve waveguide excitation efficiency. Under diode pumping, lasing has been achieved at a wavelength of 1064 nm with a slope efficiency near 15%.**

Keywords: *mixed fluoride crystals, double-clad planar optical waveguides, lasing.*

1. Introduction

Passive and active planar optical waveguides find application in various areas of optics and quantum electronics. The theory of planar waveguides (PWs) was developed in the 1980s, and the basic types of planar structures were proposed in those years and put in practice later [1]. There is particular interest in PWs based on crystals doped with trivalent rare-earth ions, which are capable of amplifying optical radiation in the visible and IR spectral regions. Note, first of all, widespread oxide laser crystals [2–5], which have well-known advantages. Fluoride crystals, which are less commonly used, are finding an ever-increasing range of applications owing to a number of their remarkable properties.

Fluoride-based laser materials offer a number of significant advantages over oxide materials, especially for producing broadband amplifiers. The fluoride laser materials have a broad transmission window, from the UV to IR spectral region (0.16–11 μm), and can be doped with high concentrations of rare-earth ions (up to 10^{21} cm^{-3}) with no significant luminescence quenching. The fluorides have a narrower phonon spectrum than do oxides, which significantly reduces the probability of multiphonon nonradiative relaxation processes and, in particular, enables highly efficient lasing in the UV, visible, near-IR and mid-IR spectral regions. These materials have lower linear and nonlinear refractive indices, which reduces the probability of various nonlinear processes at high propagating light intensities. The fluorides allow one to vary the spectroscopic properties of rare-earth ions by changing their local environment in various solid solutions. The longer level lifetimes of rare-earth ions in fluoride crystals in comparison with oxide crystals enable higher population inversion to be reached, which simplifies the development of laser amplifiers owing to the use of optical pump sources with a longer pulse duration.

Moreover, interest in fluoride-based laser materials is increasing with the development of processes for the fabrication of high-quality nanoceramics. The ability to produce fluoride nanoceramics offers additional advantages over single crystals with the same composition owing to the higher mechanical strength and fracture toughness of the nanoceramics. The fabrication of nanoceramics through powder consolidation or severe plastic deformation of crystals makes it possible to obtain nanoceramics of laser optical quality [6, 7].

Konyushkin et al. [8] reported the use of severe plastic deformation for producing ceramic and crystalline weakly guiding planar optical waveguides with core–cladding refractive index differences down to 10^{-4}. For operation in the spectral range 0.2–5 μm, they fabricated waveguides with one or several cores based on CaF_2, SrF10^{-4} and BaF10^{-4} fluoride ceramics and crystals and their solid solutions doped with trivalent Nd ions, as well as on LiF crystals containing colour centres. They presented the first results on the lasing performance of diode-pumped ceramic $SrF_2:NdF_3$ waveguides.

One drawback to the weakly guiding PWs thus produced is the low efficiency of PW core mode excitation by incoherent radiation from a laser diode, in particular, from that coupled to a multimode fibre segment. Accordingly, lasing efficiency in Ref. [8] was as low as 4%. To improve the fibre excitation efficiency, Grudinin et al. [9] proposed and demonstrated a double-clad waveguide design. The same idea was used later by Beach et al. [5] in creating PWs.

The purpose of this work was to produce a double-clad PW for improving the excitation efficiency for a waveguide having a core based on trivalent rare-earth (Nd) doped fluoride crystals and a predetermined lasing wavelength. We thought it important to compare, under identical conditions, the efficiencies of master oscillators based on diode-pumped two-layer and three-layer (double-clad) waveguides.

2. Double-clad PWs

As the gain medium of a PW laser, we used mixed yttrofluorite crystals with the composition CaF_2 + 12 wt % YF_3 + 1 wt % NdF_3. The lasing performance [10] and spectroscopic properties of such crystals [11–14] have been studied previously. Disordered yttrofluorite crystals have broad, inhomogeneously broadened absorption and luminescence bands, similar to those of neodymium laser glasses (the Nd^{3+} $^4F_{3/2} \rightarrow {}^4I_{9/2}$ luminescence spectrum is presented in Fig. 1). This makes such crystals potentially attractive for producing

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frequency-tunable laser amplifiers, including short-pulse amplifiers. It is expected that the output of a master oscillator based on a PW with a crystalline yttrofluorite core can be amplified in a laser amplifier. For this purpose, a glass amplifier is well suited. For example, phosphate glass has a gain bandwidth above 150 cm^{-1}, with a peak gain wavelength $\lambda \sim$ 1050–1053 nm [15]. The spectral positions of bands and the intensity maxima in the luminescence spectra of yttrofluorite crystals and phosphate glass differ little, suggesting that efficient light amplification would be expected.

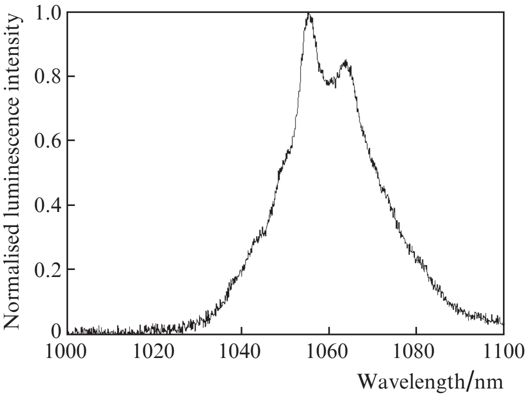

Figure 1. Nd^{3+} $^4F_{3/2} \rightarrow {}^4I_{11/2}$ luminescence spectrum of a CaF_2 + 12 wt % YF_3 + 1 wt % NdF_3 yttrofluorite crystal.

In producing PWs via severe deformation [8], we used a core and reflective cladding from crystals or nanoceramics of the same composition: CaF_2 or SrF_2. A refractive index difference $n_1 - n_2$ between the PW core (n_1) and cladding (n_2) was ensured by doping the core with NdF_3 (~0.5 mol %). The core and cladding materials were close in refractive index ($n_1 - n_2 \sim 10^{-3}$–10^{-4}) and, accordingly, in thermal expansion coefficient (TEC), which made it possible to obtain a uniform waveguide structure by sintering the core and cladding plates. A different situation occurs in the case of three-layer PWs from materials differing in TEC.

In producing double-clad PWs, high core excitation efficiency will be ensured by the largest possible refractive index difference between the core and second (outer) reflective cladding, $n_1 - n_3$, or accordingly by a large numerical aperture of the waveguide: NA = $(n_1^2 - n_3^2)^{1/2}$. In such a three-layer waveguide, the refractive index difference between the core and first reflective cladding, $n_1 - n_2$, determines the number of modes guided in the core, like in the two-layer waveguide design.

The core in our PW had the form of polished plates from a CaF_2 + 12 wt % YF_3 + 1 wt % NdF_3 yttrofluorite crystal 15–20 mm in length and 0.2–21.4 mm in thickness (n_1 = 1.4343). The second reflective cladding was made from 10-mm-thick polished LiF crystals with a refractive index n_3 = 1.391 (at λ = 633 nm). As the first reflective cladding, we used a thin polymer layer 3–6 μm in thickness (Fig. 2). The refractive index of this layer, $n_2 < n_1$, was determined from the measured numerical aperture NA = $(n_1^2 - n_2^2)^{1/2}$ = 0.05 under excitation by the 633-nm He–Ne laser line [8]. The refractive index difference $n_1 - n_2$ was 8.8×10^{-4}.

As a result, in addition to considerably increasing the total numerical aperture of the waveguide, NA = $(n_1^2 - n_3^2)^{1/2}$, the second reflective cladding should significantly increase the core mode excitation efficiency owing to the overlap of excited modes of the second cladding and core modes. The measured numerical aperture of the two-layer waveguide is NA = $(n_1^2 - n_2^2)^{1/2} \approx 0.05$, and the numerical aperture of the three-layer waveguide is NA = $(n_1^2 - n_3^2)^{1/2} \approx 0.16$. According to a rough estimate, the increase in core mode excitation efficiency in going from the two-layer to three-layer multimode PW design is proportional to the ratio of the squares of these numerical apertures, yielding ~10.

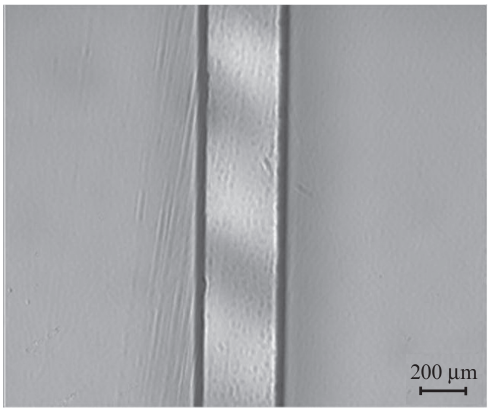

Figure 2. Microscope image of the facet of the waveguide structure: the core is a CaF_2 + 12 wt % YF_3 + 1 wt % NdF_3 plate, the first reflective cladding is a polymer layer, and the second reflective cladding is a crystalline LiF plate.

3. Lasing performance

The lasing performance was studied using the same optical scheme as previously [8]. The above PW, based on an yttrofluorite crystal, was placed in a resonator ~35 mm in length, formed by a flat dichroic mirror and a concave output coupler with a 50-mm radius of curvature. The reflectivity of the output coupler at the lasing wavelength was 95%, and the input (dichroic) mirror had a near 100% reflectivity at the lasing wavelength and high transmission at the pump wavelength (λ = 795 nm). As a pump source, we used a fibre-pigtailed laser diode with a core diameter of 120 μm. The pulsed 795-nm laser diode output (pulse duration, 3 ms; pulse repetition rate, 10 Hz) was focused by a spherical lens (f = 8–12 mm) into the PW core through the flat dichroic mirror.

This laser, based on a 15-mm-long three-layer PW with a core thickness of 1.4 mm, emitted at λ = 1064 nm. Figure 3 shows its output power as a function of incident pump power. The actual pump power, absorbed in the PW core, is substantially lower than the incident power because of the waveguide loss and the mismatch between the focusing system of the pump laser and the numerical aperture of the PW. The measured slope efficiency of the laser (~15%) considerably exceeds the efficiency (4%) obtained by us with an identical optical scheme under the same pump conditions for a two-layer PW laser having a 0.2-mm-thick, 7-mm-wide $SrF_2 : NdF_3$ (0.5 mol %) ceramic core and a crystalline SrF_2 reflective cladding. The efficiency reached in this study approaches that obtained for a laser with an optimised $SrF_2 : Nd^{3+}$ crystal, whose maximum slope efficiency with respect to absorbed pump power was 24%. It is also worth noting that the slope efficiency with respect to incident pump power for an yttrofluorite single crystal in a similar configuration was 11%, i.e. even lower than that of the PW laser (Fig. 3).

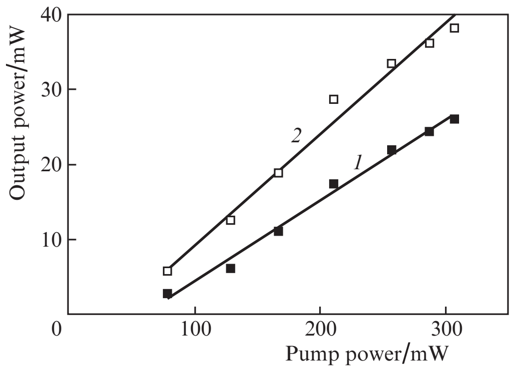

Figure 3. Output laser power as a function of incident pump power for (*1*) a crystal and (*2*) a PW with a neodymium-doped yttrofluorite core.

Figure 4 shows measured emission spectra of a laser with a gain element based on an yttrofluorite single crystal or PW. It is seen that the laser emission spectra of the single crystal and PW have a maximum at λ = 1064 nm, which allows this radiation to be effectively used for subsequent amplification, e.g. in amplifiers based on silica glass or yttrium aluminium garnet crystals. The spectra have a periodic structure. Note that reducing the thickness of the PW core from 1.2 mm to 220 μm led to a considerable decrease in laser emission bandwidth (Fig. 4b), but the periodic structure persisted. This may be related to the effect of core thickness on the number of generated modes and mode frequency spacing in PWs.

Thus, we have produced double-clad three-layer PWs with a crystalline CaF_2 + 12 wt % YF_3 + 1 wt % NdF_3 core. Under diode pumping, lasing was achieved at λ = 1064 nm with a slope efficiency near 15%.

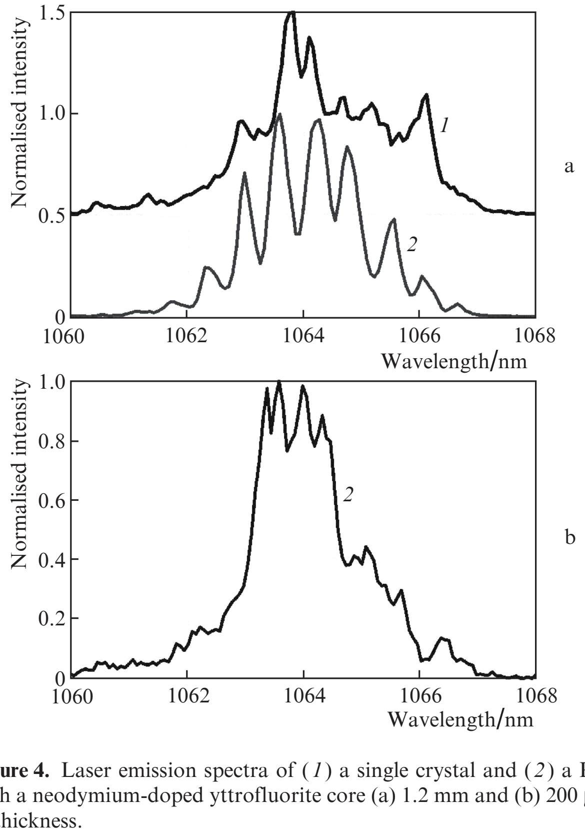

Figure 4. Laser emission spectra of (*1*) a single crystal and (*2*) a PW with a neodymium-doped yttrofluorite core (a) 1.2 mm and (b) 200 μm in thickness.

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