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Planar waveguide structures based on SrF_2: Ho, Er, Tm. Dependence of the refractive index on the dopant concentration

A.Ya. Karasik, V.A. Konyushkin, A.N. Nakladov, D.S. Chunaev

Abstract. **Refractive indices of SrF_2 crystals doped with holmium, erbium, and thulium ions are measured. These crystals are used as active laser media, in particular, as materials for planar waveguides. The presence of active ions in these crystals may create a difference between the refractive indices of the cladding and the doped core of a planar waveguide. At dopant concentration to 4 %, the difference Δn between the refractive indices of the doped core and undoped reflective layer can reach 0.007.**

Keywords: *strontium fluoride, refractive indices.*

Interest in planar optical waveguides (WGs) as active laser media is caused by their advantages compared to bulk media. In [1, 2], we reported on the development of methods for fabricating planar ceramic and crystalline waveguides based on alkali and alkali-earth fluorides doped with trivalent ions of rare-earth (RE) elements. The aim of this work is to study RE-doped materials for using them to fabricate active planar waveguides and achieve laser amplification in the near-IR spectral region.

In [1], planar waveguides were made using hot pressing. In this case, the core plate made of fluoride ceramics or crystal with preliminarily polished two faces was sandwiched between two polished plates serving as reflective layers. This three-layer structure was pressed by uniaxial hot pressing. This method of fabrication of planar waveguides has some specific features. The use of crystals with considerably different thermal expansion coefficients (TECs) for the active core and the reflective cladding may lead to additional stresses at the interface between the two waveguide media upon cooling of the structure after hot pressing.

Therefore, as core and cladding materials, it is preferable to use crystals with identical structures and close TECs. A difference in the refractive indices of the core and cladding can be achieved by introducing various impurities in both the core and the reflective cladding of the waveguide expecting that low dopant concentrations will not considerably change the TECs. In addition, this approach makes it possible to smoothly change the difference between the core and cladding refractive indices. Of particular interest is to change the refractive index of transparent crystals by introduction of RE impurities that may, in addition, play the role of laser-active dopants.

To increase the PW excitation efficiency, we proposed and demonstrated in [2] a three-layer waveguide structure with a double reflective cladding and a core based on fluoride crystals doped with trivalent Nd ions. The first reflective cladding was a polymer layer 3–6 μm thick, while the second reflecting cladding consisted of a LiF crystal plate with a thickness of hundreds of micrometers. Note that the formation of the first polymer cladding in such three-layer PWs considerably simplifies the problem of stresses in the interface layers. As a result, the use of the second reflective cladding in the developed PW, in addition to a considerable increase in the total numerical aperture of the waveguide, led to a considerable increase in the core mode excitation efficiency due to the overlap of the fields of excited modes of the second cladding and core. Estimates show that an increase in the core mode excitation efficiency of a three-layer multimode PW with respect to a two-layer PW is proportional the ratio of the squares of their numerical apertures.

The laser characteristics of hot-pressed active PWs of the first type based on SrF_2 ceramics with a neodymium-doped core were studied in [1].

Changes in the refractive index of SrF_2 crystals due to doping with different RE fluorides were studied in [3]. In fact, these crystals are two-component solid solutions $(1 - x)SrF_2 + xRF_3$, where R is a rare-earth element. The single-component SrF_2 crystal structure is similar to the structure of CaF_2 fluorite; solid solutions $(1 - x)SrF_2 + xRF_3$ at $x < 0.5$ also have a fluorite structure. The refractive index of the SrF_2 crystal at wavelength $\lambda = 589$ nm (yellow Fraunhofer line D) is $n = 1.438$ [3], while the refractive index of RF_3 crystals is considerably higher ($n \approx 1.60$). Thus, introduction of an RE fluoride as the second component into the SrF_2 crystal leads to an increase in the refractive index.

In [3], changes in the refractive index of the SrF_2 crystal were studied with addition of large (exceeding 10 mol %) amounts of RE fluorides. These concentrations of the second component caused pronounced changes in the refractive index (to $\Delta n \sim 0.02$). In the present work, we measured the refractive indices of strontium fluoride containing small concentrations of RE elements, which are usually used for laser-active media. These measurements were performed using an URL-2 refractometer, which allows one to measure refractive indices of liquids and solids at the Fraunhofer line D with an accuracy up to 0.0002.

We measured the refractive indices of fluoride strontium crystals doped with Ho, Er, and Tm, which are used as active ions for laser amplification. The high-quality crystals were grown by the Bridgman method from melt in a fluorinating

A.Ya. Karasik, V.A. Konyushkin, A.N. Nakladov, D.S. Chunaev
A.M. Prokhorov General Physics Institute, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: karasik@lst.gpi.ru, chunaev@lst.gpi.ru

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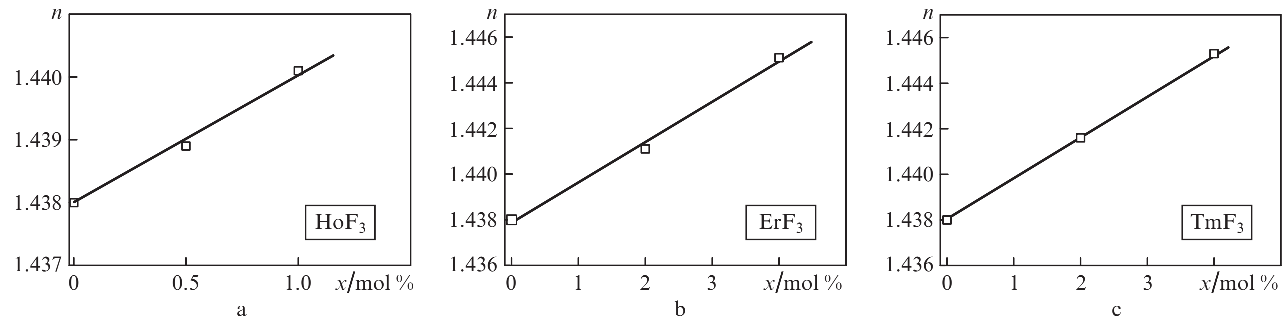

Figure 1. Dependence of the refractive index of $(1 - x)SrF_2 + xRF_3$ crystals on concentrations of (a) HoF_3, (b) ErF_3, and (c) TmF_3.

Table 1. Experimental refractive indices of crystalline samples.

Sample	Composition	Refractive index at λ = 589 nm
0	SrF_2	1.4380 ± 0.0002
1	SrF_2 + 2% Tm	1.4416 ± 0.0002
2	SrF_2 + 4% Tm	1.4453 ± 0.0002
*	SrF_2 + 10.2% Tm	1.458 ± 0.001
3	SrF_2 + 0.5% Ho	1.4389 ± 0.0002
4	SrF_2 + 1% Ho	1.4401 ± 0.0002
*	SrF_2 + 10% Ho	1.458 ± 0.001
5	SrF_2 + 2% Er	1.4411 ± 0.0002
6	SrF_2 + 4% Er	1.4451 ± 0.0002
*	SrF_2 + 9.7% Er	1.457 ± 0.001

* Note: data are taken from [3].

atmosphere. For measurements, we made samples in the form of parallelepipeds with a length of ~20 mm and transverse dimensions of 5×5 mm. All surfaces of the samples were polished.

The measured refractive indices are presented in Table 1. We plotted dependences of refractive indices of SrF_2 crystals on concentration x of RF_3 fluorides (R = Ho, Er, Tm). The measurement results are shown in Fig. 1. The experimental dependences of refractive indices n in the used range of RF_3 concentrations are well approximated by linear functions.

The obtained data show that the refractive index of RE-doped strontium fluoride crystals can be controlled by slightly changing the RE concentration, which makes it possible to develop planar waveguides with the core and reflective cladding made of one and the same fluoride. This opens the possibility of controlling the properties of planar waveguides, namely, numerical aperture and number of excited modes.

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