Spectral properties of laser planar waveguides based on fluoride ceramics and crystalline solid solutions

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Abstract. The spectral characteristics of the fluorine planar waveguides of the type of \(\text{Me}_1\text{F}_2-\text{Me}_2\text{F}_3\) created by the hot-forming method with the refractive index difference between the active medium (core) and the reflective shell no more than \(10^{-2}-10^{-4}\) are investigated. A planar waveguide with a core of mixed neodymium fluorite crystals \(\text{CaF}_2-\text{NdF}_3:\text{Nd}^{3+}\) with a double reflecting cladding of \(\text{LiF}\) to increase the excitation efficiency of the waveguide has shown that fluoride-based laser materials have a number of significant advantages in comparison with oxide materials, especially when creating wide-range amplifiers. With powerful lateral pumping of waveguides by matrices of laser diodes with a wavelength near 0.8 \(\mu\)m and a power more than 1 kW, luminescence was observed both at the same wavelength and at two wavelengths simultaneously (near 0.9 and 1.05 \(\mu\)m), which makes it possible to control their spectroscopic properties.

1. Introduction

The waveguide theory of planar waveguides began to develop actively in the 1980s. At the same time, the main types of planar structures were proposed, and then implemented in practice. The appearance in the last decade of powerful laser diodes for pumping of solid-state laser media, the expansion of their spectral range, has increased the interest in the creation and investigation of new types of planar optical waveguides. This is due to the fact that active laser media in the form of planar waveguides have several advantages over bulk laser media. Such advantages of planar waveguides as a large length of interaction of radiation with the medium, preservation of linear polarization of laser radiation, compactness are of considerable interest for photonics [1, 2].

Of particular interest are planar waveguides based on matrices activated by trivalent rare-earth ions, which can enhance optical radiation in the wide visible and infrared regions of the spectrum. Earlier, we investigated lasers with self-reversal of the wave front in media with different configurations of the active medium (round rods, rectangular rods and others) [3, 4]. A waveguide self-phase conjugate laser is being developed and studied for the first time. It differs in that waveguide modes are formed in a planar planar active element (AE). These modes can compete with the modes of laser radiation propagating in free space. The competition of modes can increase the instability of generation from pulse to pulse and distort the transverse structure of the radiation beam.
2. Test setup

Fluoride laser ceramics were used as the active medium of a laser based on planar waveguides using the composite structure of CaF$_2$–NdF$_3$:Nd$^{3+}$ (1 wt. %). They have the properties of a disordered crystal, that is, they have wide inhomogeneously broadened absorption and luminescence spectra. This makes these crystals promising when creating frequency tunable laser amplifiers, including short pulse amplifiers.

In the experiments we used an active element with an activated part (core) with dimensions: 7 mm in width, 56 mm in length and 2 mm in height (Fig. 1). Planar, activated by Nd$^{3+}$ ions, the core is located between two non-activated parts (cladding). All the surfaces of the active element had an optical quality of processing for the implementation of side or face diode pumping.

Pumping of the AE was carried out by diode arrays of the SLM-3-3 type (“Inject”, Saratov) with a radiating pad measuring 25×2 mm. The nominal wavelength of the radiation was 795 nm. The maximum radiation power reached 1500 W at a pump pulse of 250 μs duration. The frequency of the pump pulses was set to 1-30 Hz.

To study the luminescent properties of a laser active medium, a test setup was created (Fig. 2). The test setup included an optical laser pumping system using semiconductor laser diode arrays, an optical collimating focusing system and an AE mounting and mounting assembly on a liquid-cooled base, and also in the study of luminescent properties, two mirrors forming a laser resonator (not shown on Fig. 2).

When laser optical pumping could use the following combinations: one or two matrices for one-sided pumping, two or four matrices simultaneously for two-sided pumping. The pump matrices were connected to a specially manufactured multichannel electric power supply system (“FEDAL”, St. Petersburg).

The optical collimation-focusing system (Fig. 3) was constructed on the basis of flat-convex cylindrical lenses (Edmund Optics Inc., USA) with a focal length of 50 (PCX 25×50 type) and 25 mm (PCX 25×25 type). This made it possible to create an image of the radiating areas of pumping matrices approximately 2 mm in height for the most complete and uniform illumination of the internal volume along the cross section of the planar AE based on CaF$_2$–NdF$_3$:Nd$^{3+}$ (2 mm in height).
In the future, we developed (Fig. 4,a) and manufactured (Fig. 4,b) using additive technology (3D printer ULTIMAKER 2 plus, at BSTU “VOENMEKH”) mock-up of a quantron with a two-sided system focusing of the pump radiation in the AE.

### 3. Fluorescent properties of fluoride laser ceramics

All rare-earth ions are characterized by the presence of narrow luminescence lines on transitions between the states of the 4f shell and intense absorption bands at the $4f \rightarrow 5d$ transitions used for

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**Fig. 2. Test stand for fluoride active elements**

1 – laser pumping system with semiconductor diodes; 2 – optical system of transportation and focusing of pump radiation; 3 – cooled base for mounting AE

**Fig. 3. Optical collimation-focusing system based on flat-convex cylindrical lenses**
pumping. The energy position of its levels depends little on the type of matrix, since the unfilled shell 4f is well shielded from external fields by 5s and 5p electrons and the influence of the crystal field on the active ion is small. The most widely used activator at present are Nd$^{3+}$ ions [5, 6, 7].

A spectroscopic scheme of the Nd$^{3+}$ ion is known. The optical and laser properties of the trivalent neodymium ion are determined by transitions inside the 4f electron shell. In the crystal, all levels of a free ion undergo a splitting due to the Stark effect when interacting with intracrystalline field. Each term is split into $(2J + 1)/2$ components, that is, the $^4I_{11/2}$ level splits into 6 sublevels, $^4I_{13/2}$ by 7, $^4I_{9/2}$ by 5. The metastable upper level of the working transition is the $^4F_{3/2}$ level. The lower level of the working transition can be represented by any of the levels of $^4I_{9/2} - ^4I_{15/2}$ multiplets. The basic level is the set of sublevels of the lower multiplet $^4I_{9/2}$.

All transitions are made from one level $^4F_{3/2}$, consisting of two sublevels. The most probable are 3 generation lines: $^4F_{3/2} \rightarrow ^4I_{13/2}$ (about $\lambda = 1.3 \, \mu m$), $^4F_{3/2} \rightarrow ^4I_{11/2}$ (about $\lambda = 1.06 \, \mu m$) and $^4F_{3/2} \rightarrow ^4I_{9/2}$ (about $\lambda = 0.9 \, \mu m$).

In active media with different crystal matrices, the rare-earth ions differ by the cross section of the transitions and the coefficients of branching of the luminescence. Even in the strongest transitions of the same matrix, there are large differences in for transitions between the Stark sublevels, hence, the signal amplification coefficients in the active medium and the laser generation threshold will be different.

Traditionally, optical radiation is used for optical pumping with wavelengths of 808 or 880 nm. This radiation transfers Nd$^{3+}$ ions from the ground state $^4I_{9/2}$ to a series of $^4F_{3/2}$ or $^4F_{5/2}$ excited states, respectively. These levels consist of a large number of narrow, partially overlapping levels arising from the splitting of terms in the electric field of the crystal lattice of crystals.

Ceramics of CaF$_2$–NdF$_3$: Nd$^{3+}$ has wide bands in its absorption spectrum (Fig. 5). The main bands are 740, 795 and 870 nm. Measurements have shown that effective pumping can also be carried out also in 3 bands, and the lines 730, 800, 810 and 860 nm can be considered as dominant in them (Fig. 5,b). The width of the pumping bands is from 10 to 40 nm. This not only greatly simplifies the optical laser pumping, but also allows one to vary the radiative parameters of the active medium with a mixed structure.

![Fig. 4. Designed (a) and fabricated (b) with the use of additive technology, a prototype of a quantron with focusing of the pump radiation into the activated region of the planar active element](image-url)
Fig. 5. Absorption spectrum of a laser active element based on ceramics $\text{CaF}_2$-$\text{NdF}_3$:Nd$^{3+}$
Fig. 6. The radiation spectrum of a matrix of diodes and luminescence of laser ceramics
The spectral characteristics of CaF$_2$–NdF$_3$:Nd$^{3+}$ ceramics were determined using a highly sensitive optical spectrophotometer “AvaSpec-2048” (the highest photometric sensitivity corresponds to a spectral range of 200–1100 nm at an optical resolution of 0.04 nm). For this purpose, a prototype of a quantron with an AE (Fig. 4) was placed in a plane-parallel resonator formed by a deaf (reflection close to 1) and output (reflection less than 0.1) by the end mirrors.

With intense (more than 1 kW) lateral optical narrow-band diode pumping of AE from CaF$_2$–NdF$_3$:Nd$^{3+}$ at 795 nm, intense luminescence is observed at both one wavelength 1055 nm. An increase in the pump wavelength from 795 to 800 nm (Fig. 6) by synchronously changing the temperature of the thermostatting of the pump matrices leads to the appearance of an additional luminescence band gradually increasing in intensity at a wavelength of 903 nm (Fig. 6,b). This indicates the possibility of controlling the spectroscopic properties and the possibility of obtaining two-wave generation in a resonator of a special design.

References
[1] Konyushkin V A, Nakladov A N, Konyushkin D V, Doroshenko M E, Osiko V V, Karasik A Ya 2013 Quantum Electronics 43 60.
[2] Grishutkina T E, Doroshenko M E, Karasik A Ya, Konyushkin V A, Konyushkin D V, Nakladov A N, Osiko V V, Tsvetkov V B 2015 Quantum Electronics 45 717.
[3] Burkovsky G V, Fedin A V, Pogoda A P, Boreysho A S 2016 Quantum Electronics 46 976.
[4] Pogoda A P, Sergeev A A, Fedin A V, Ivanov A S, Nikiforov N V 2017 Pisma v GTF 43 86.
[5] Svelto O 1998 Principles of Lasers (Springer New York Dordrecht Heidelberg London).
[6] Koechner W 1996 Solid-State Laser Engineering (New York, “Springer-Verlag”).
[7] Weber M J 2001 Handbook of lasers (CRC press).