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Design and Characterization of Resonator Mirrors for Microlasers on the Base of $YAlO_3$ Single Crystals Activated with Nd^{3+} and Tm^{3+} Ions

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Most of the challenges in laser technology can be overcome by using yttrium-aluminum perovskite ($YAlO_3$, YAP). These crystals are characterized by more advantages than typical $Y_3Al_5O_{12}$ (YAG) crystals. However, the creation of microlasers with these materials is just under development. The aim of the work was to theoretically design the input and output cavity mirrors for microlasers on the base of $YAlO_3$:Nd or $YAlO_3$:Tm single crystals, and to investigate those resonators obtained according to the theoretical design using electron beam evaporation method.

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1. Introduction

Downsizing the equipment in laser technology is faced with essential challenges. One of ways of getting over these challenges is to create microchip lasers and microlasers having the cavity mirrors inserted into the working surface of an active element. In this case the structure of mirrors requires special calculations for each active medium, and investigations into their properties, first of all the resistance to irradiation.

Many research papers are known to be dedicated to designing and investigating the microchip lasers and microlasers based on different single crystal materials, such as: epitaxial structures vanadates [1], borates [2] or $Gd_3Ga_5O_{12}$:Nd/$Gd_3Ga_5O_{12}$:Cr^{4+}. However, the most widely used materials in creating microlasers and microchip lasers are $Y_3Al_5O_{12}$:Nd crystals [3–6]. At the same time, many problems faced in laser technology, including the creation of microlasers, can be resolved through the use of the yttrium-aluminum perovskite ($YAlO_3$, YAP) crystals.

With the main physical properties of the YAP crystals being close to the properties of the YAG crystals, the yttrium aluminum perovskite has a number of advantages compared to the garnet crystals: natural birefringence due to which the thermally-induced birefringence does not compromise its laser features, linearly polarized laser irradiation, more than 100 K lower melting point; several fold increase of distribution coefficient neodymium into a crystal structure; as well as for the YAP crystals as opposed to YAG ones the so-called core, is not inherent [7–9].

The YAP crystals are not free of disadvantages, the most significant of which are the twinning and the creation of growth-induced color centers. However, these disadvantages can be eliminated through designing of the appropriate thermal assemblies of the growth setups and through the annealing of the crystals after the growth in an appropriate atmosphere [10, 11].

In lasers based on $YAlO_3$:Nd crystals the most used are generation wavelengths of 1.079 μm and 1.342 μm. The 1.079 μm wavelength finds a use similar to the radiation of YAG:Nd crystals with a wavelength of 1.064 μm. The radiation with a wavelength of 1.342 μm is of interest due to its applications for medical purposes [12]. The second harmonic (671 nm) can be applied in the exhaust gas analyzers for the automobile diesel engines [13], and for pumping of the frequency-tunable lasers on crystals doped with Cr^{3+}.

Radiation in the range of 2 μm is successfully used in the Doppler lidars [14], range finders, and in analysis of the water vapour content [15]. Application of the lasers activated with thulium ions becomes promising for medical purposes [16]. These can also be an effective source for pumping the optical parametric oscillators (OPO) to convert the frequencies in the range of 3–12 μm [17]. For the time being, one of the most promising active mediums to create the lasers generating in a range of 2 μm are the $YAlO_3$:Tm crystals [18].

However, regardless of that the $YAlO_3$ crystals are widely used in laser technology, the creation of microlasers using these materials is only at the development stage. Thus, among the tasks of current importance are

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those related to designing the multilayer dielectric mirrors to be deposited onto the surfaces of the microlaser active elements made of yttrium orthoaluminate, as well as their properties study.

This work was intended to calculate theoretically the input and output mirrors for microlasers based on the YAP:Nd and YAP:Tm crystals, and to obtain, by the electron-beam evaporation method, a mirror experimental model to study their reflection spectra and damage threshold.

2. Research method

The crystals investigated were grown by the Czochralski method according to the process described in [10]. Grinding and polishing of the crystals, under the requirements for the laser quality, were performed on the production line of the "Logitech" company (GB). The crystal surface roughness was controlled using the "Dektak" profilometer (USA). The crystal surface flatness was determined using the "Logitech" interferometer G-120. Application of the developed mechanical working techniques allowed to achieve $R_Z < 0.05$ and a flatness of less than one Newton's ring.

Calculation of the thin-film structures of the dielectric mirrors was performed using the software: *Berechnung und Optimierung von dielektrischen Spiegeln–Version 0.22 by A. Stark.* This software realizes a matrix method of analysis to determine the optical thickness of the structure layers providing constant the refractive indexes of the layers (n_i), of the substrate (n_s) and of the external medium (n_0). The optimization parameters were the reflective index (R) at pumping and generation wavelengths, as well as the desired number of the structure layers.

The mirrors were deposited using the electron-beam evaporation setup of the "TORR" company (USA), with the thickness of a deposited layer being controlled by a quartz resonator.

The reflection spectra of the obtained mirrors were registered using the UV3600 spectrophotometer of the "Shimadzu" company (Japan).

The damage threshold of the mirrors exposed to laser irradiation was determined using a setup based on the pulsed laser LTI-237 with $\lambda_{\text{gen}} = 1064$ nm, the pulse duration $\tau_{\text{pulse}} = 6$ ns, and the pulse energies $E_{\text{pulse}} =$ 5–50 mJ.

3. Results and discussion

The resonator mirrors are covered by the requirements for: the refractive indexes of the layers (n_i) of which they are made of, their adhesion, stability during evaporation, and damage threshold. With this in mind and based on the experience in creating the external mirrors of the resonators for gas and solid-state lasers [19, 20], the following materials were used to create the mirrors: SiO_2 (material with n_i less than n of $YAlO_3$) and HfO_2 (material with greater n_i).

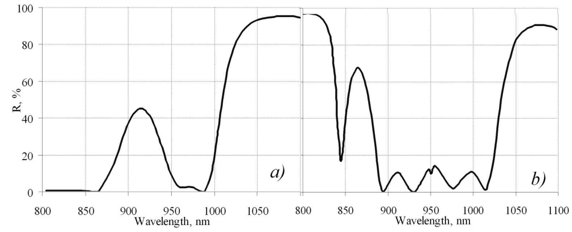

Fig. 1. Calculation of reflection spectra for input (a) and output (b) mirrors of cavity for $YAlO_3$:Nd with $\lambda_{\text{gen}} = 1.079$ μm.

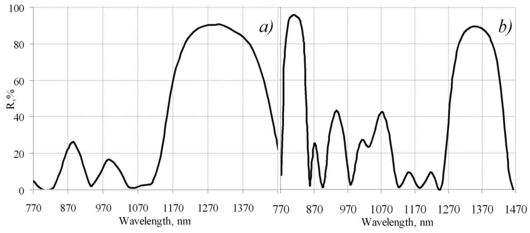

Fig. 2. Calculation of reflection spectra for input (a) and output (b) mirrors of cavity for $YAlO_3$:Nd with $\lambda_{\text{gen}} = 1.342$ μm.

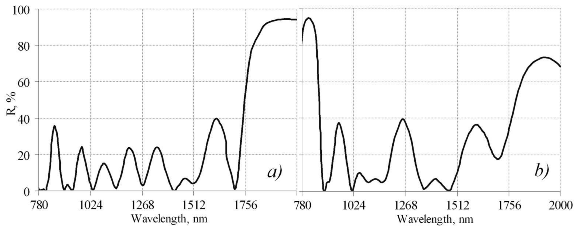

Fig. 3. Calculation of reflection spectra for input (a) and output (b) mirrors of cavity for $YAlO_3$:Tm with $\lambda_{\text{gen}} = 1.94$ μm.

The calculation results are given in Table below. Figures 1–3 show the reflection spectra of the mirrors.

In order to verify the theoretical calculations, the input mirror was evaporated onto the surface of the $YAlO_3$:Nd crystal for $\lambda_{\text{pump}} = 0.808$ μm, and $\lambda_{\text{gen}} = 1.079$ μm. Evaporation was performed with the chamber's pumped-out volume of 5×10^{-6} mmHg, and by adding the oxygen into the chamber up to a pressure of 4×10^{-4} mmHg under the following modes: substrate temperature — 200 °C; evaporator–substrate distance — 400 mm; evaporation rate for HfO_2 and ZrO_2 layers — 1.75–2.0 Å/s, SiO_2 layer — 4.0 Å/s; average number of layers — 13–17 with a sum thickness of 3.3–3.9 μm.

The reflection spectrum of the structure obtained was practically the same as the calculated one.

After evaporation the multilayer dielectric mirror was exposed to the pulses of laser irradiation with the pulse energies of: 18, 16, 14, 12, 10 and 8 mJ. This made possible to find out that the surface is damaged when impacted by a pulse whose energy exceeds 10 mJ. Taking

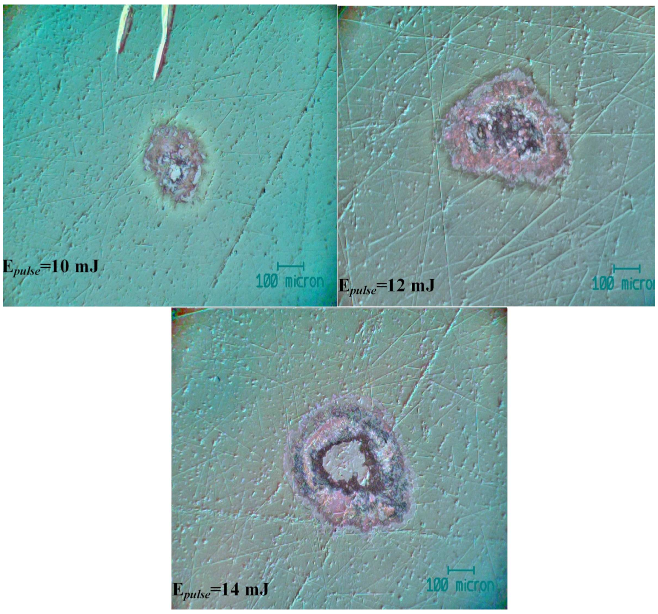

Fig. 4. Damage of the surface of the $YAlO_3$ crystal after pulse laser irradiation.

into account the pulse duration (6 ns) and the waist diameter of the laser beam focused (280 μm), the oriented boundary power density is equal to 3 GW/cm^2. Figure 4 provides the photos of the damaged areas of a multilayer dielectric mirror.

4. Conclusions

This paper provides the newly made calculations for the design of multilayer dielectric mirrors based on SiO_2 and HfO_2 layers, for the resonators of microlasers based on the crystals of $YAlO_3$:Nd (at: $\lambda_{\text{pump}} = 0.808$ μm, $\lambda_{\text{gen}} = 1.079$ μm and 1.342 μm) and of $YAlO_3$:Tm (at: $\lambda_{\text{pump}} = 0.795$ μm, $\lambda_{\text{gen}} = 1.940$ μm). The calculation data are well correlated with the experimentally obtained reflection spectra of the mirrors deposited by the electron-beam evaporation. Investigations on the damage threshold of the input mirror for a microlaser based on $YAlO_3$:Nd (for $\lambda_{\text{pump}} = 0.808$ μm and $\lambda_{\text{gen}} = 1.079$ μm), when exposed to pulse irradiation at a wavelength of 1.064 μm, showed that the damage is observed at $E_{\text{pulse}} > 10$ mJ ($\tau_{\text{pulse}} = 6$ ns), which, under the applied experiment geometry, corresponds to a power density of 3 GW/cm^2.

TABLE

Properties of designed mirrors.

Substrate material	Type of mirror	λ_{pump} [μm]	λ_{gen} [μm]	R_{pump} [%]	R_{gen} [%]	Number of layers	Sum thickness [nm]
$YAlO_3$:Nd	input	0.808	1.079	0.51	95.40	15	4355.5
$YAlO_3$:Nd	output	0.808	1.079	96.99	90.90	16	4893.3
$YAlO_3$:Nd	input	0.808	1.342	0.022	91.27	13	3308.5
$YAlO_3$:Nd	output	0.808	1.342	95.36	90.69	16	4781.2
$YAlO_3$:Tm	input	0.795	1.940	0.64	94.54	15	4215.7
$YAlO_3$:Tm	output	0.795	1.940	94.63	72.84	14	3384.7

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