

Heat conduction of laser vanadate crystals

A.I. Zagumennyi, P.A. Popov, F. Zerouk, Yu.D. Zavartsev, S.A. Kutovoi, I.A. Shcherbakov

Abstract. The heat conduction of laser vanadate crystals GdVO_4 and YVO_4 and their solid solutions is measured in the temperature interval from 50 to 350 K. Mixed rare-earth vanadates have the common chemical formula $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$, where Re' and Re'' are two or more types of ions from a series La^{3+} , Pr^{3+} , Nd^{3+} , Sm^{3+} , Eu^{3+} , Gd^{3+} , Tb^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , Tm^{3+} , Yb^{3+} , Lu^{3+} , Sc^{3+} , Y^{3+} . The heat conduction of Nd:YVO_4 measured at room temperature proved to be more than twice higher than that reported in the literature and in certificate characteristics of laser Nd:YVO_4 elements manufactured by numerous commercial companies. The empirical dependences of the heat conduction along the crystallographic axes $\langle 100 \rangle$ and $\langle 001 \rangle$ on the composition of rare-earth vanadates $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$, are obtained in the temperature interval from 200 to 350 K.

Keywords: heat conduction, vanadates, laser crystals.

1. Introduction

The heat conduction of a crystal is one of the most important parameters determining the efficiency of using this crystal in flashlamp- and diode-pumped lasers. A Nd:YAG crystal has become the most popular crystal in previous years for applications in flashlamp-pumped lasers to a considerable degree due to its high heat conduction. And although the spectral and luminescence parameters of many crystals were much better than those of the Nd:YAG crystal and they were cheaper, their heat conduction was lower. At present many diode-pumped commercial lasers use Nd:YVO_4 crystals, which are now more widely applied than Nd:YAG crystals. Laser vanadate crystals doped with Yb^{3+} ions can find wide applications in science and technologies in the near future.

Highly efficient lasing in diode-pumped Nd:GdVO_4 crystals was first demonstrated in paper [1], and later

efficient lasers emitting in the IR region [2], green, red [3], and blue [4] spectral regions were developed. The heat conductions of Nd:GdVO_4 and Nd:YAG crystals in the temperature range from 77 to 300 K are presented in paper [5], and of a Tm:GdVO_4 crystal – in paper [6]. The heat conduction of a gadolinium vanadate crystal depends on the crystallographic direction and is $11.7 \text{ W m}^{-1} \text{ K}^{-1}$ in the $\langle 101 \rangle$ direction at 300 K. This value exceeds the heat conduction of an yttrium–aluminium garnet crystal doped with Nd at the atomic concentration 1% ($11.1 \text{ W m}^{-1} \times \text{K}^{-1}$). Highly efficient lasing at a wavelength of 1060 nm in a mixed lanthanum–gadolinium $\text{Nd:Gd}_{0.5}\text{La}_{0.5}\text{VO}_4$ crystal was first studied in paper [7]. Compared to all other combinations of rare-earth elements, a laser $\text{Gd}_{0.5}\text{La}_{0.5}\text{VO}_4$ crystal has the maximum period of the zirconium-structure crystal lattice, resulting in the maximum width of the luminescence band of neodymium ions. This was the main prerequisite for studying a $\text{Nd:Gd}_{0.5}\text{La}_{0.5}\text{VO}_4$ crystal.

The parameters of $\text{Nd:Gd}_x\text{Y}_{1-x}\text{VO}_4$ mixed vanadate crystals used in various diode-pumped lasers have been studied in papers published in recent years. The radiation of low-power cw lasers based on Nd:YVO_4 and Nd:GdVO_4 vanadate crystals and mixed vanadate crystals has close output parameters, while some differences between the data reported by different authors can be explained by variations in the optical quality of laser elements. However, the radiation of passively Q -switched mixed vanadate lasers [8, 9] had better output parameters compared to that of Nd:YVO_4 and Nd:GdVO_4 lasers. In [10], a 1175-nm Raman laser based on $\text{Nd:Gd}_x\text{Y}_{1-x}\text{VO}_4$ crystals with $x = 0, 0.2, 0.4, 0.6, 0.8$, and 1.0 was studied. The cw lasing efficiency of all these crystals was the same within $\pm 5\%$; however, Raman lasing was obtained only in $\text{Nd:Gd}_{0.8}\text{Y}_{0.2}\text{VO}_4$ and $\text{Nd:Gd}_{0.6}\text{Y}_{0.4}\text{VO}_4$ crystals.

From the point of view of crystal-chemistry classification, $\text{Nd:Gd}_x\text{Y}_{1-x}\text{VO}_4$ mixed vanadate crystals represent a small part of a series of numerous solid solutions. Mixed rare-earth vanadates have the general chemical formula $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$, where Re' and Re'' are two or more ions from a series of La^{3+} , Nd^{3+} , Sm^{3+} , Eu^{3+} , Gd^{3+} , Tb^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , Tm^{3+} , Yb^{3+} , Lu^{3+} , Sc^{3+} , Y^{3+} . Laser matrices based on mixed vanadates can consist of two, three and more optically inactive ions, for example, the $\text{La}_x\text{Y}_y\text{Gd}_k\text{Lu}_v\text{Sc}_z\text{VO}_4$, where $x + y + k + v + z = 1$, $0 \leq x \leq 0.5$, $0 \leq y \leq 1$, $0 \leq k \leq 1$, $0 \leq v \leq 1$, $0 \leq z \leq 1$. A variety of mixed vanadates is the result of the 100% isomorphic mutual substitution of rare-earth ions Gd^{3+} , Lu^{3+} , Sc^{3+} , and Y^{3+} by preserving the structural type of the

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crystal lattice. For La^{3+} ions, the value $x = 0.5$ should not be exceeded; otherwise, the crystal changes its structural type and transforms from a uniaxial crystal to a biaxial one. This considerably restricts the possibility of its applications in medical and technological lasers.

A wide variety of chemical compositions of mixed vanadate matrices along with a broad range of concentrations of traditional activating ions Nd^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , Tm^{3+} , Yb^{3+} permits the synthesis of many new laser crystals based on mixed vanadates. This raises the question of the choice of a criterion for estimating the possibility of using one or another of the crystals to obtain lasing. This criterion should predict the compositions of laser crystals that are not promising for real technological applications. Vanadate crystals are grown in expensive iridium crucibles. An obligatory requirement for obtaining highly efficient lasing is the use of an individual iridium crucible for each activating ion because even traces of impurities reduce the lasing efficiency or completely quench lasing. In the 1980–1990s, hundreds of papers devoted to the study of solid-state lasers based on garnets of various compositions and their solid solutions were published. However, due to their low heat conduction, these crystals cannot compete with a YAG crystal in applications for commercial lasers used in medicine and technology.

In this paper, we obtained the empirical dependences of the heat conduction along crystallographic axes $\langle 100 \rangle$ and $\langle 001 \rangle$ on the composition of rare-earth vanadate crystals $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$ in the temperature range 200–350 K. The calculation of the heat conduction of new laser mixed vanadate crystals is proposed to predict the possibility of their successful technological applications before proceeding to expensive experiments on the crystal growth and studying their spectral, luminescent, and lasing parameters.

2. Experimental

All vanadate crystals and their solid solutions were grown in iridium crucibles of diameter 40–80 mm by the Czochralski method in industrial Kristal-2 and Kristal-3m setups. The extra pure (99.99 %) initial reagents were used, which is obligatory for growing laser vanadate crystals. Technological parameters employed in growing these crystals and their solid solutions are close, and therefore we used the same parameters as in growing $\text{Nd}:\text{GdVO}_4$ [1, 2]. Crucibles of diameter 80 mm allowed the growth of crystals of diameter up to 60 mm and length 120 mm. The diameter and length of activated crystals were 25–40 mm and 60–80 mm, respectively.

Rods for measuring the heat conduction in different crystallographic directions and laser elements for diode- or flashlamp-pumped lasers were cut out from crystalline boules. The optical quality of the crystals was controlled visually with a microscope for observing the scattering of a 633-nm laser beam by microscopic defects (Fig. 1). No scattering centres were observed in these crystals. The high quality of the crystals was confirmed by lasing experiments with diode pumping. Thus, the slope lasing efficiency of the $\text{Nd}:\text{YVO}_4$ and $\text{Nd}:\text{GdVO}_4$ crystals at a wavelength of 1 μm was 60 % and 65 %, respectively, while the slope efficiency of the $\text{Nd}:\text{Gd}_{0.7}\text{Y}_{0.3}\text{VO}_4$ crystal was 71 %.

The heat conduction was measured by the stationary method of a longitudinal heat flow. Single-crystal samples were rectangular rods of cross section 3×5 mm cut out in

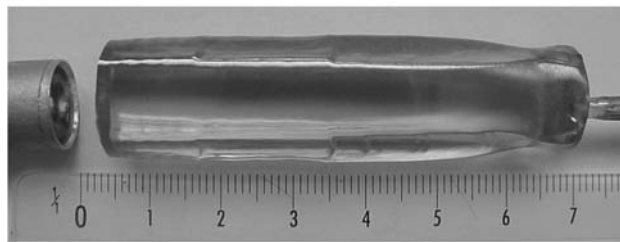


Figure 1. $\text{Nd}:\text{GdVO}_4$ crystal illuminated by a laser for quality control.

different crystallographic directions. The length of samples was 30–40 mm, and temperature sensors (differential chromel–copel–iron thermocouples) were separated by ~ 18 –20 mm. The temperature drop along a sample during measurements did not exceed 1.5 K. Estimates performed taking into account possible sources of experimental errors and the reproducibility of the data obtained, as well as the results of measurements of the heat conduction of calibrated reference brass samples restrict the measurement error of the heat conduction in the temperature interval from 50 to 350 K by the value 5 %.

3. Results and discussion

The heat conduction, being a practically important physical property of matter, depends on many factors such as the type of a crystal lattice, lattice defects, the strength of chemical bonds, the ion mass, and temperature. For this reason the heat conduction of laser dielectric crystals cannot be calculated theoretically and can be measured only experimentally.

Table 1 presents the heat conduction of rare-earth vanadate matrices and laser crystals measured in the temperature interval from 50 to 350 K. The results of our measurements of the temperature dependence of the heat conduction of a $\text{Nd}:\text{YAG}$ crystal are also given for comparison. Thus, we can correctly compare the heat conduction of new laser vanadate crystals with that of the main commercial laser crystal. It has been found earlier [5] that the heat conduction of gadolinium vanadate depends on the crystallographic direction and is $11.7 \text{ W m}^{-1} \text{ K}^{-1}$ in the $\langle 101 \rangle$ direction at 300 K, which exceeds the heat conduction of $\text{Nd}(1\%):\text{YAG}$ equal to $11.1 \text{ W m}^{-1} \text{ K}^{-1}$.

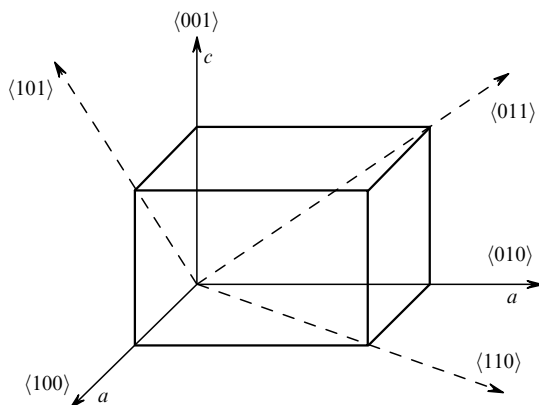
The crystallographic axes are strictly oriented in laser elements made of GdVO_4 , YVO_4 vanadate crystals and numerous $\text{La}_x\text{Y}_y\text{Gd}_{k-x-y-v-z}\text{Lu}_y\text{Sc}_z\text{VO}_4$ solid solutions with the zirconium structure (the $I4_1/amd$ space group). In most cases upon diode pumping, the crystallographic axis c of the laser element is oriented perpendicular to the optical axis of the laser, while the crystallographic axis a coincides with the optical axis of the laser. Figure 2 shows the orientation of crystallographic axes of vanadate samples during heat conduction measurements. The zirconium structure belongs to the tetragonal syngony and therefore the physical properties of zirconium along the a and b axes are identical. For this reason, both these axes are denoted as the a axis in Fig. 2.

The heat conduction θ_c along the c axis (the $\langle 001 \rangle$ direction) for vanadate crystals of all compositions exceeds its value θ_a along the a axis (the $\langle 100 \rangle$ and $\langle 010 \rangle$ directions).

Table 1. Experimental heat conceptions (in $\text{W m}^{-1}\text{K}^{-1}$) of vanadate crystals.

| Direction | Crystal composition | Impurity (atomic concentration) | Temperature/K | | | | | | | | |
|-----------------------|--|---------------------------------|---------------|------|------|------|------|------|------|------|------|
| | | | 50 | 60 | 80 | 100 | 150 | 200 | 250 | 300 | 350 |
| $\langle 001 \rangle$ | GdVO_4 | no | 160 | 106 | 64 | 44.4 | 25 | 18 | 14.5 | 12.3 | 10.8 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.99}\text{Nd}_{0.01}\text{VO}_4$ | 1% Nd | 115 | 86 | 54 | 38 | 22.5 | 16.6 | 13.4 | 11.7 | 10.5 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.99}\text{Sc}_{0.01}\text{VO}_4$ | 1% Sc | 155 | 110 | 65 | 46 | 25.7 | 17.4 | 14.0 | 12.0 | 10.7 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.99}\text{Ca}_{0.01}\text{VO}_4$ | 1% Ca | 148 | 105 | 61 | 43 | 23.7 | 16.8 | 13.9 | 12.5 | 11.3 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.98}\text{Sc}_{0.01}\text{Nd}_{0.01}\text{VO}_4$ | 1% Nd + 1% Sc | 110 | 82 | 55 | 39 | 23.3 | 17 | 13.5 | 11.7 | 10.5 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.98}\text{Sc}_{0.02}\text{VO}_4$ | 2% Sc | 148 | 109 | 64 | 43 | 25 | 17.5 | 13.9 | 11.5 | 10.5 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.93}\text{La}_{0.028}\text{Y}_{0.028}\text{Sc}_{0.01}\text{VO}_4$ | 2.8% La + 2.8% Y + 1% Sc | 66 | 50 | 35.3 | 27 | 18.3 | 14 | 11.7 | 10.0 | 9.0 |
| $\langle 100 \rangle$ | $\text{Gd}_{0.997}\text{Nd}_{0.01}\text{VO}_4$ | 1.3% Nd | – | – | – | – | 20 | 14.3 | 11.5 | 9.6 | 8.5 |
| $\langle 100 \rangle$ | $\text{Gd}_{0.99}\text{Sc}_{0.01}\text{VO}_4$ | 1% Sc | 135 | 97 | 57 | 38 | 20.7 | 14.8 | 11.5 | 9.6 | 8.4 |
| $\langle 101 \rangle$ | $\text{Gd}_{0.99}\text{Sc}_{0.01}\text{VO}_4$ | 1% Sc | 158 | 100 | 60 | 41 | 22.5 | 16 | 12.7 | 10.8 | 9.4 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.927}\text{Tm}_{0.0685}\text{Ho}_{0.0046}\text{VO}_4$ | 6.85% Tm + 0.46% Ho | 53 | 42 | 30.4 | 24.3 | 16.9 | 13.3 | 11.4 | 10.0 | 8.9 |
| $\langle 001 \rangle$ | $\text{Gd}_{0.92}\text{Tm}_{0.08}\text{VO}_4$ | 8% Tm | 49 | 39 | 29 | 23.3 | 16.5 | 13.2 | 11.2 | 9.8 | 8.8 |
| $\langle 001 \rangle$ | $\text{Y}_{0.993}\text{Nd}_{0.007}\text{VO}_4$ | 0.7% Nd | 118 | 82 | 53 | 39 | 24.3 | 18.3 | 15 | 13.0 | 10.9 |
| $\langle 001 \rangle$ | $\text{Y}_{0.892}\text{Yb}_{0.1}\text{Tm}_{0.008}\text{VO}_4$ | 10% Yb + 0.8% Tm | 21.8 | 18.5 | 15.2 | 13.5 | 11.4 | 10.5 | 9.6 | 9.2 | 8.7 |
| $\langle 100 \rangle$ | $\text{Y}_{0.99}\text{Sc}_{0.01}\text{VO}_4$ | 1% Sc | 172 | 113 | 63 | 40.5 | 21.7 | 15 | 12 | 9.8 | 8.5 |
| $\langle 001 \rangle$ | $\text{Y}_{0.995}\text{Nd}_{0.005}\text{VO}_4$ | 0.5% Nd | 155 | 109 | 66 | 47 | 28 | 20.5 | 16.8 | 14.5 | 13.0 |
| $\langle 110 \rangle$ | $\text{Y}_{0.995}\text{Nd}_{0.005}\text{VO}_4$ | 0.5% Nd | 97 | 66 | 43 | 31 | 18 | 13.3 | 10.8 | 9.4 | 8.4 |
| $\langle 110 \rangle$ | $\text{Gd}_{0.5}\text{Y}_{0.455}\text{Tm}_{0.08}\text{VO}_4$ | 45.5% Y + 8% Tm | 17.2 | 14 | 11.1 | 9.2 | 7.3 | 6.3 | 5.8 | 5.4 | 5.2 |
| $\langle 111 \rangle$ | $\text{Y}_{2.97}\text{Nd}_{0.027}\text{Al}_5\text{O}_{12}$ | 0.9% Nd | 166 | 127 | 72 | 47 | 25 | 17.0 | 13.1 | 11.1 | 10.1 |

The heat conduction in the $\langle 100 \rangle$ and $\langle 010 \rangle$ directions virtually coincides with that in the $\langle 110 \rangle$ direction. These facts are a consequence of the $I4_1/amd$ crystal structure, and therefore there is no need to measure the heat conduction in different crystallographic directions in uniaxial vanadate crystals. For practical applications of vanadate crystals in lasers, it is necessary to know the heat conduction in two directions (along the c and a axes) in the operating temperature range of the laser element between 50 and 350 K. By extrapolating the temperature dependences of the heat conduction, it is possible to calculate the heat conduction at high temperatures, which can be produced within the region pumped by focused radiation from high-power diode lasers.

**Figure 2.** Scheme of the orientation of crystallographic axes of vanadate samples in heat conduction measurements.

At the initial stage of data processing, we analysed the correlation of the heat conduction of vanadates with the fundamental properties of crystals such as the period and volume of the crystal cell, the mean radius of ions in the dodecahedral site, and the relation between the atomic mass of the matrix ion in the dodecahedral site and the atomic mass of impurity rare-earth ions. We have failed to find the explicit dependence of the heat conduction on these parameters of vanadate crystals within the measurement accuracy in the temperature interval from 180 to 350 K.

An unambiguous understanding of the notation of the chemical composition of mixed vanadate crystals is important in practical applications of these crystals. Some papers use the notation $\text{Nd}:\text{Gd}_x\text{Y}_{1-x}\text{VO}_4$, whereas the others use the notation $\text{Nd}:\text{Y}_x\text{Gd}_{1-x}\text{VO}_4$. This raises the question: Which of the matrices, YVO_4 or GdVO_4 , is considered as the host and, therefore, which of the elements, Y or Gd, is treated as impurity? A similar situation appears for complex $\text{La}_x\text{Y}_y\text{Gd}_{k-x-y-v-z}\text{Lu}_v\text{Sc}_z\text{VO}_4$ mixed vanadate crystals. From the crystal-chemistry point of view, any matrix can be chosen as the host, for example, a GdVO_4 matrix, while all the other rare-earth ions can be treated as impurities formed due to the isomorphic mutual substitution of Gd^{3+} ions. Similarly, a YVO_4 matrix can be chosen as the host. In this case, the composition of all vanadate crystals can be described by the formula $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$, in which $0 \leq x \leq 1$ and one or more ions from a series of La^{3+} , Nd^{3+} , Sm^{3+} , Eu^{3+} , Gd^{3+} , Tb^{3+} , Dy^{3+} , Ho^{3+} , Er^{3+} , Tm^{3+} , Yb^{3+} , Lu^{3+} , Sc^{3+} , Y^{3+} can be impurity elements. Such an approach allows one, by abstracting from particular chemical elements, to write the chemical formula for rare-earth vanadates in the form $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$, in which the subscript x determines quantitatively the lattice defect affecting the mean free path of thermal phonons and,

therefore, exerts the decisive effect on the heat conduction of crystals of the given composition. In this connection we assume that the subscript x in the formula $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$ will allow us to obtain the empirical dependence of the heat conduction on the crystal composition. In other words, we assume that the heat conduction of various rare-earth vanadate crystals mainly depends on the relation between rare-earth elements in the crystal. This assumption is basic in our paper. It is justified to some extent because the crystal structure of rare-earth vanadate consists by 83% of vanadium and oxygen ions forming tetrahedral anion complexes.

The chemical formula of a crystal in Table 1 is written so that the basic element stands at the first place and the subscript x determines the number of impurity rare-earth ions. If, for example, a GdVO_4 matrix is chosen as the host, we have $x = 0$ for a GdVO_4 crystal, $x = 0.02$ for a $\text{Gd}_{0.98}\text{Sc}_{0.01}\text{Nd}_{0.01}\text{VO}_4$ crystal, etc. According to this formalised approach, the chemical composition of a pure YVO_4 matrix logically follows from the formula $\text{Gd}_{1-x}\text{Y}_x\text{VO}_4$ for $x = 1$, i.e. $x = 1$ corresponds to the composition $\text{Gd}_0\text{Y}_1\text{VO}_4$.

Any pure initial reagent Gd_2O_3 or Y_2O_3 contains microscopic impurities of all rare-earth elements, and therefore the composition of the YVO_4 and GdVO_4 laser crystals can be written in the form $\text{Gd}_{1-x-y-v-z}\text{La}_x\text{Y}_v\text{Lu}_y\text{Sc}_z\text{VO}_4$, where one subscript is approximately unity, while all the others are close to zero, but are nonzero. Impurity ions in the $\text{Gd}_{1-x}\text{Re}'_x\text{VO}_4$ compounds listed above are represented by various rare-earth elements; however, the subscript x characterises only the concentration of an element, but not its chemical type. According to such an approach, the most important parameter is only the total amount of impurities rather than the type of a chemical element. Therefore, two compositions, for example, the $\text{Y}_{0.892}\text{Yb}_{0.1}\text{Tm}_{0.08}\text{VO}_4$ and $\text{Y}_{0.892}\text{Gd}_{0.108}\text{VO}_4$ crystals have the same value $x = 0.108$, as follows from the formula $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$. Moreover, one can write down a great number of chemical compositions for which $x = 0.108$. In this case, according to the assumption proposed above, all vanadate crystals with this subscript x will have approximately the same heat conduction θ_c along the c axis and the same heat conduction θ_a along the a axis.

The dependence of the heat conduction θ on the subscript x for rare-earth vanadates $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$ can be considered to be proved if the experimental values of the heat conduction along the c axis for various chemical compositions of the crystal can be described by one function $\theta = f(x)$. The choice of the function, whose parameters should be selected to describe experiments, is based on the following reasoning. Due to the 100% isomorphic mutual substitution of rare-earth ions in vanadates, the function f should be approximately symmetric with respect to its extremum. The most complete experimental data on the heat conduction of rare-earth garnet $\text{Yb}_x\text{Y}_{1-x}\text{Al}_5\text{O}_{12}$ for $0.5 \geq x \geq 0$ [11] should be described by the dependence of the same type as for rare-earth vanadates. Note that a rare-earth aluminium garnet crystal contains 85% of aluminium and oxygen ions forming tetrahedral and octahedral anion complexes, which also corresponds to our assumptions. The Holliday function $y^{-1} = (A + Bx + Cx^2)$ well satisfies the above-mentioned conditions.

Figure 3 presents the experimental dependences of the heat conduction along the c axis on the crystal composition

approximated by the Holliday function for the $\text{Yb}_x\text{Y}_{1-x}\text{Al}_5\text{O}_{12}$ garnets [11] and $\text{Y}_x\text{Gd}_{1-x}\text{VO}_4$ vanadates at room temperature. Figures 4 and 5 present heat conduction $\theta_a(x)$ along the a axis at crystal temperatures 300 and 350 K and heat conduction $\theta_c(x)$ along the c axis at temperatures 200, 250, 300, and 350 K for all vanadate crystals studied in this paper (see Table 1). The dependences of the heat conduction are also well described by the Holliday function. This means that the dependence of the heat conduction of rare-earth vanadates on their composition is determined first of all by the number of impurity rare-earth ions rather than by their type and that the mass difference of substituting ions and the presence of scattering centres in the crystal affect the heat conduction θ only in the second approximation.

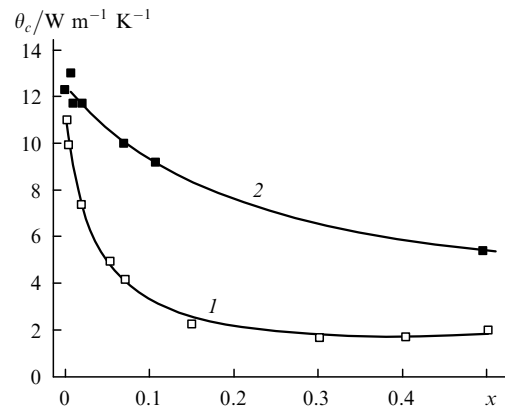


Figure 3. Dependences of the heat conduction θ_c along the c axis on the crystal composition approximated by the Holliday function for the $\text{Yb}_x\text{Y}_{1-x}\text{Al}_5\text{O}_{12}$ garnet crystal [11] (1) and the $\text{Y}_x\text{Gd}_{1-x}\text{VO}_4$ vanadate crystal (2) at room temperature.

The experimental dependences of the heat conduction along the a axis on the composition of the $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$ rare-earth vanadate crystal presented in Fig. 4 have the form

$$\theta_a = (0.1 + 0.38x - 0.42x^2)^{-1} \quad \text{at } T = 300 \text{ K}, \quad (1)$$

$$\theta_a = (0.11 + 0.41x - 0.5x^2)^{-1} \quad \text{at } T = 350 \text{ K}. \quad (2)$$

The experimental values of the heat conduction along the c axis at different temperatures are described by the Holliday function only for $T > 200$ K, i.e. the adopted assumption is valid only at high temperatures. At temperatures 200–350 K, the calculated and experimental values of the heat conduction are in good agreement, which is an important practical result of our paper. For example, the heat conduction θ_c calculated for vanadates with $x = 0.5$ is $\sim 5.5 \pm 0.2 \text{ W m}^{-1}\text{K}^{-1}$. Therefore, mixed $\text{Re}'_{0.5}\text{Re}''_{0.5}\text{VO}_4$ vanadates have the minimum heat conduction, which has a small anisotropy and only weakly depends on temperature in the range from 50 to 350 K. The approximation of experimental data in Fig. 5 gives the following dependences of the heat conduction along the c axis for rare-earth $\text{Re}'_{1-x}\text{Re}''_x\text{VO}_4$ vanadates at different temperatures:

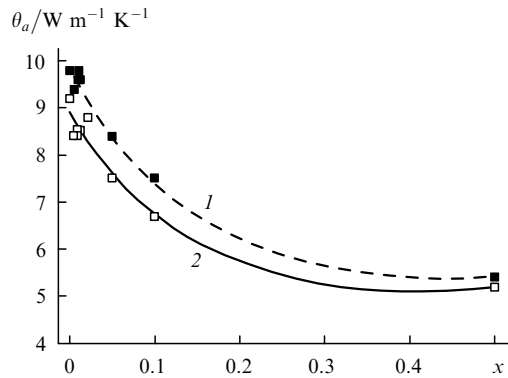


Figure 4. Dependences of the heat conduction θ_a along the a axis on the composition of a vanadate crystal measured at $T = 300$ K (1) and 350 K (2).

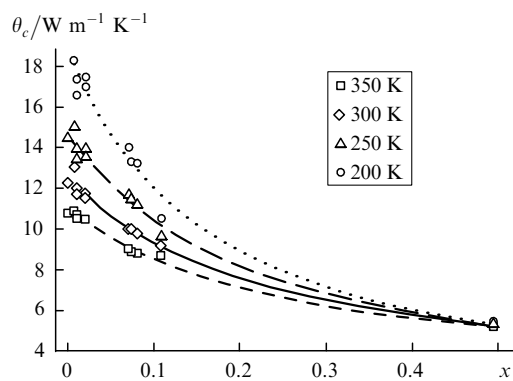


Figure 5. Dependences of the heat conduction θ_c along the c axis on the composition of a vanadate crystal measured at different temperatures.

$$\theta_c = (0.05 + 0.31x - 0.07x^2)^{-1} \text{ at } T = 200 \text{ K}, \quad (3)$$

$$\theta_c = (0.07 + 0.29x - 0.1x^2)^{-1} \text{ at } T = 250 \text{ K}, \quad (4)$$

$$\theta_c = (0.08 + 0.29x - 0.16x^2)^{-1} \text{ at } T = 300 \text{ K}, \quad (5)$$

$$\theta_c = (0.09 + 0.27x - 0.13x^2)^{-1} \text{ at } T = 350 \text{ K}. \quad (6)$$

The heating of crystals doped with Nd^{3+} , Tm^{3+} , Ho^{3+} , and Yb^{3+} ions in three-level lasers above room temperature leads to a considerable increase in the lasing threshold, and therefore it is sufficient to know the heat conduction of new vanadate crystals at $T = 300 - 350$ K for real practical calculations of the lasing efficiency.

The heat conductions of vanadate crystals presented in Table 1 show which of these crystals are promising for replacing Nd:YAG crystals in commercial lasers emitting at $1.06 \mu\text{m}$. To achieve maximum output powers and reduce the thermal lens effect, it is preferable to use monocationic GdVO_4 , YVO_4 , LuVO_4 crystal matrices doped with activating ions at low concentrations. In particular, the concentration of Nd^{3+} ions in diode-pumped high-power vanadate lasers should be $0.1\% - 0.25\%$. At such low

activator concentrations, vanadate crystals still have a sufficiently high absorption coefficient at the pump wavelength and their heat conduction only slightly decreases compared to that of the pure matrix. This is a significant advantage of vanadates compared to a Nd:YAG crystal, in which the neodymium concentration should be $0.8\% - 1\%$ to provide the required absorption coefficient.

We will estimate the heat conduction of new rare-earth vanadate laser crystals by the example of lutetium vanadate crystals. At present LuVO_4 laser crystals have not been studied yet, in particular, because of the high cost of initial reagents. However, by using the empirical dependences of the heat conduction on the crystal composition, we can predict the development of highly efficient lasers based on LuVO_4 crystals activated with neodymium, thulium, and ytterbium ions. For example, the calculated heat conduction θ_c along the $\langle 001 \rangle$ axis for lutetium vanadate doped with Nd^{3+} , Tm^{3+} , and Yb^{3+} ions is $11.7 \text{ W m}^{-1} \text{ K}^{-1}$ for $\text{Lu}_{0.99}\text{Nd}_{0.01}\text{VO}_4$, $10.8 \text{ W m}^{-1} \text{ K}^{-1}$ for $\text{Lu}_{0.95}\text{Tm}_{0.05}\text{VO}_4$, and $11.5 \text{ W m}^{-1} \text{ K}^{-1}$ for $\text{Lu}_{0.98}\text{Yb}_{0.02}\text{VO}_4$. The heat conduction of these laser crystals is higher than that of the corresponding YAG crystals, which suggests that Nd:LuVO₄, Tm:LuVO₄, and Yb:LuVO₄ crystals are promising for applications in low-, moderate-, and high-power lasers.

4. Conclusions

We have studied the heat conduction of laser vanadate crystals GdVO_4 and YVO_4 and their solid solutions in the temperature range between 50 and 350 K. The calculated and experimental heat conductions are in good agreement in the temperature range between 200 and 350 K. The heat conduction of a Nd:YVO₄ crystal measured at room temperature proved to be more than twice higher than the value presented in the literature and certificate characteristics of Nd:YVO₄ laser elements manufactured by numerous commercial companies.

Mixed vanadate crystals $\text{R}'_{0.5}\text{Re}''_{0.5}\text{VO}_4$ have the low heat conduction, which weakly depends on temperature, and a small anisotropy of the heat conduction along the crystallographic axes.

The dependence of the heat conduction on the crystal composition is determined first of all by the number of impurity rare-earth ions rather than by their type.

To achieve maximum output powers and reduce the thermal lens effect, it is preferable to use monocationic GdVO_4 , YVO_4 , and LuVO_4 crystal matrices doped with activating ions at low concentrations.

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