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Possibilities of Using Modern Infrared Imaging Devices for Measuring the Temperature of the Lasing Regions of Solid-State Lasers Pumped with High-Power Laser Diodes

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Abstract—The modern infrared imaging technique is applied to studies of the temperature fields and heat loads of Er:YAG laser crystals under conditions of optical pumping of these crystals with high-power (20 W) radiation from diode arrays with fiber outputs. It is shown that state-of-the-art infrared imagers operating in the range 8–14 μm can be efficiently used to monitor the near-surface temperatures in the lasing regions of solid-state lasers under high-power diode pumping. The possibilities of modern infrared imagers for evaluating the degree of heating of the lasing region in a laser crystal, the temperature distribution in this region, and the efficiency of operation of cooling systems and for preliminarily rejecting active laser elements have been demonstrated.

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INTRODUCTION

In recent years, much attention has been given to the development of high-power small solid-state lasers (SSLs), in which high-power laser-diode arrays are used as pumping sources (LD pumping).

The use of LD pumping allows a substantial increase in the laser efficiency and creation of high pump-power densities in the lasing region. Owing to this circumstance, laser systems allowing attainment of a radiation power of tens and hundreds of watts in lasing regions with sizes of several cubic millimeters are currently being developed [1, 2].

It is natural that, at such parameters, the questions of the temperature conditions of these systems become extremely important. Simple estimates show that, in the absence of an efficient cooling system, lasing regions may be overheated by several hundred degrees. This will result in both degradation of the lasing characteristics of crystals (in most laser materials, they deteriorate with an increase in the temperature) and misalignment of a laser system owing to the formation of thermal lenses. Another problem is that a laser crystal may contain inhomogeneities, which will lead to the formation of local overheated regions. The appearance of such defects causes degradation of crystals and a decrease in their radiation resistance.

To solve the aforementioned problems, various cooling systems for laser crystals are being developed. Naturally, to determine the values of overheating and evaluate the efficiency of operation of cooling systems, it is desirable to use methods to measure the temperature of lasing regions directly in the process of crystal pumping. In addition, it is desirable that these methods also allow recording of the temperature distribution in the lasing regions. It is clear that the use of standard contact methods for this purpose is either difficult or excluded. In this study, we present the possibilities of using modern IR imaging facilities in solving this problem.

EXPERIMENTAL TECHNIQUES AND SYSTEMS

Modern IR imagers are analogues of video cameras operating in the IR but not in the visible region. They are based on photodetector arrays operating in the IR range (as a rule, 3–5 or 8–12 μm) [3]. Because the main portion of thermal radiation at $T = 300$–600 K is concentrated within these ranges, these devices can be used for both visualizing heated objects and measuring their temperature.

Modern IR imagers have formats of 256 × 256, 320 × 240, 512 × 512, or more elements, and their sensitivity is several percent of a degree. They operate in a television mode (at a data acquisition rate of several tens of hertz). The mathematical provision of this class of instruments ensures temperature measurements with an accuracy of a few fractions of a degree.

This study was performed using IR imagers of two types: ЛИК-2 domestic IR imagers operating in the wavelength range 3–5 μm and instruments produced by NEC (Japan) (TH-9100 and TH-7800 series) operating at 8–14 μm. Both cameras had approximately the same format (256 × 256 elements in the ЛИК-2 and 320 × 240 in the NEC) and sensitivity (several per-

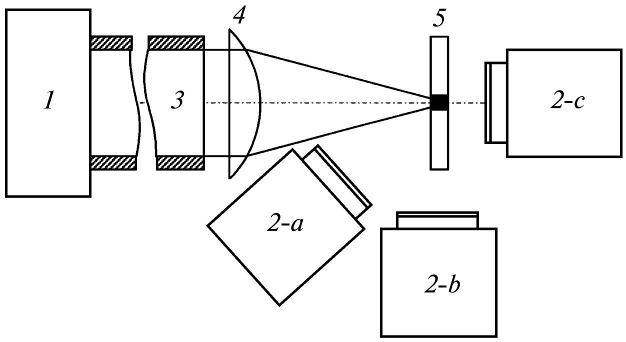

Fig. 1. Block diagram of the experimental setup: (*1*) diode pumping unit, (*2*) IR imaging camera in different positions (*a*, *b*, and *c*) relative to a laser crystal, (*3*) optical fiber, (*4*) pumping-beam focusing system, and (*5*) YAG:Er^{3+} laser crystal.

cent of a degree). The cameras operated in a television mode at a data acquisition rate of 25 and 60 Hz, respectively. A YAG:Er^{3+} crystal (with a concentration of Er ions $C = 50\%$), which was pumped with an LIMO32-F400-DL980 diode array with a radiation-outputting fiber (at a wavelength $\lambda = 975$ nm and a power $P = 20$ W) was taken as an object under study.

YAG:Er^{3+} crystals are transparent in the region 3–5 μm (the absorption coefficient in this region is $\alpha \approx (2–5) \times 10^{-4}$ cm^{-1} [4]) and virtually opaque in the region 8–12 μm. Therefore, the devices operating at wavelengths of 8–12 μm can detect radiation and measure the temperature in the lasing regions adjacent to the crystal surface. The use of devices sensitive to wavelengths of 3–5 μm also allows detection of thermal radiation from the sample bulk and, in principle, temperature measurements within the entire lasing region. However, in this case, it is difficult to determine the absolute temperature values.

In fact, samples with low absorption coefficients have correspondingly low emissivities, thus impairing the accuracy of temperature measurements almost in all cases. In our situation, the problem is aggravated by the fact that the absorption of the lasing channel and,

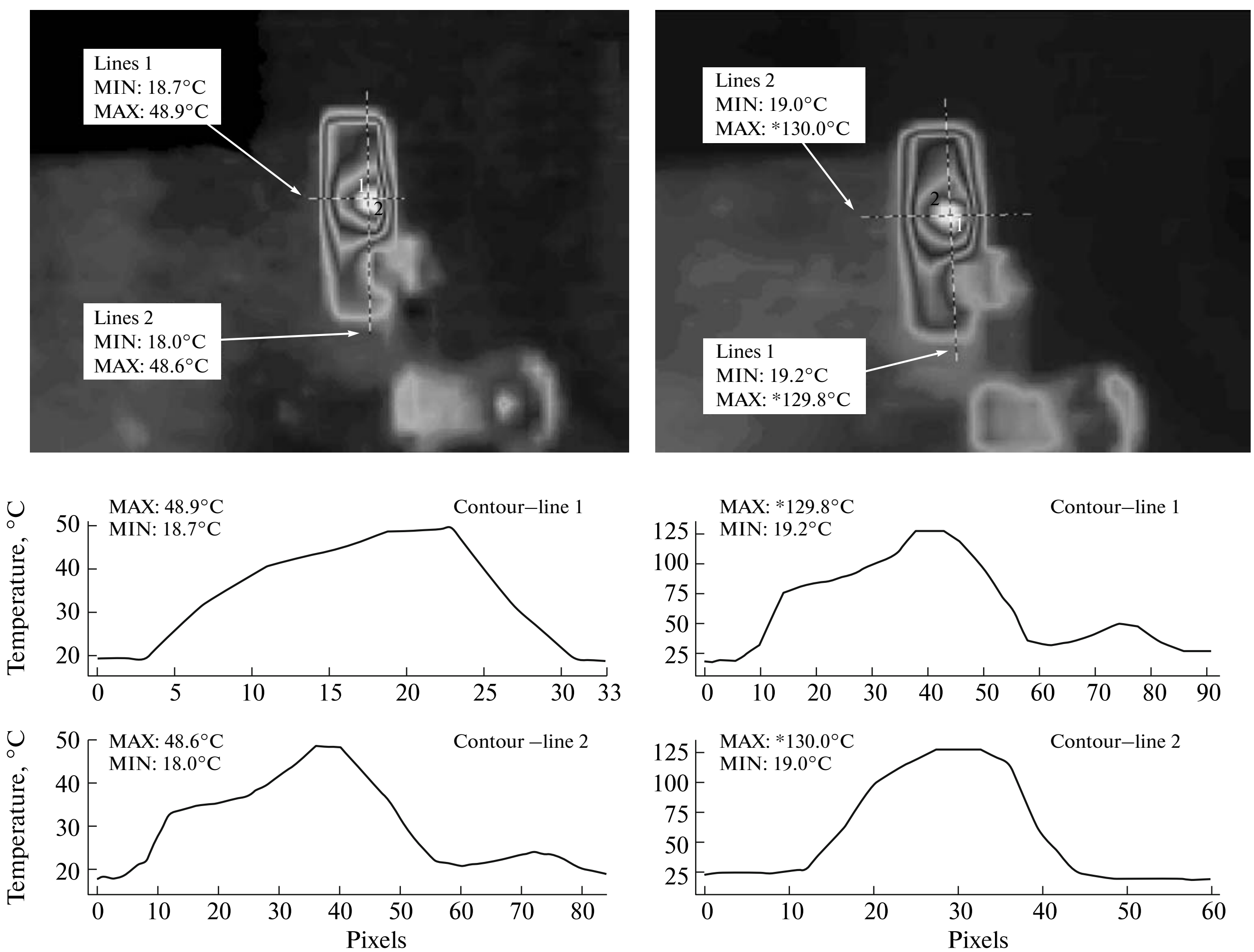

Fig. 2. Thermograms of YAG:Er^{3+} crystals at different pumping-power levels measured in geometry *a*.

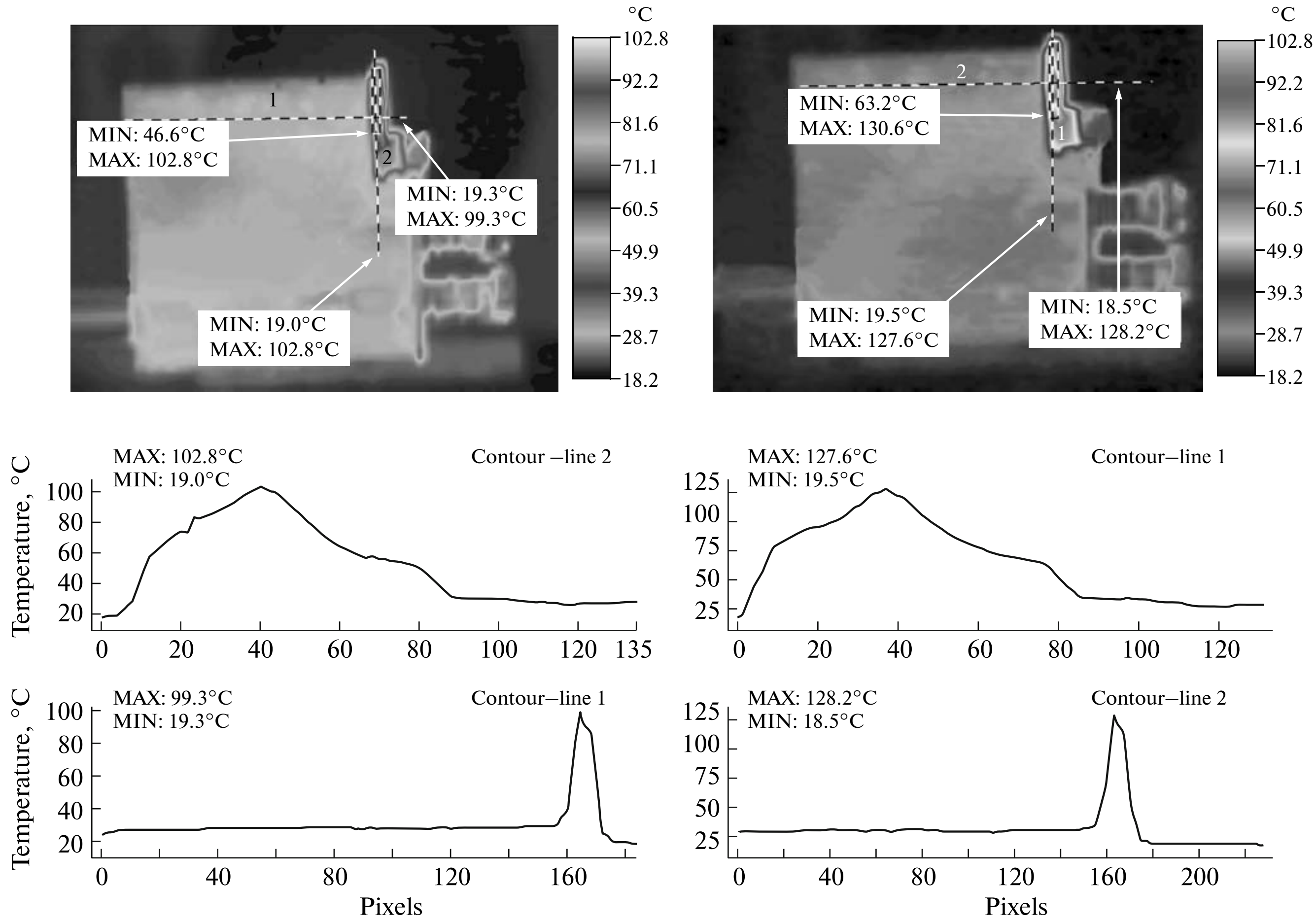

Fig. 3. Thermograms of $YAG{:}Er^{3+}$ crystals at different pumping-power levels measured in geometry *b*.

correspondingly, the value of the emissivity in the range 3–5 μm depend on the pumping power. This considerably complicates the problem of measuring the absolute temperatures. Therefore, this spectral range can most likely be used only for studying the temperature distribution in the lasing region. This is important, e.g., for detecting defects resulting in anomalously high absorption in $YAG{:}Er^{3+}$ crystals.

For prompt evaluation of the temperature of the lasing region directly in the experimental setup, the range 8–12 μm should be preferred. In this case, changes in the emissivity related to the excitation of erbium ions have a weak effect on the total emissivity, thus allowing rather accurate temperature measurements of near-surface lasing regions.

In this study, the emissivity of samples was determined using a standard technique—by fitting the value of the temperature measured with an IR imager to a temperature measured with conventional contact methods on a sample without photoexcitation. For $YAG{:}Er^{3+}$ crystals, the emissivity is 0.98 for the range 8–14 μm, whereas in the range 3–5 μm, it is several hundredths.

It is precisely these circumstances that determine the use of IR imagers operating in two spectral regions in our investigation. Correspondingly, the schemes of the experimental setups were somewhat different.

Figure 1 shows a schematic of the experiment with the use of an ЛИК-2 IR imager (for the range 3–5 μm). The dimensions of the $YAG{:}Er^{3+}$ crystal were 10 × 5 × 1 mm. LD pumping radiation was focused into a strip with a size of 0.4 × 5.0 mm approximately in the middle of the crystal. The IR imager was placed on an optical bench at a distance of ~25 cm from the sample (position *c*). Approximately 50% of the pumping power was absorbed by the $YAG{:}Er^{3+}$ crystal. After passing through the sample, the LD pumping radiation was defocused, and its part incident on the IR imager was absorbed by its IR filters and did not affect the results of the experiment.

A slightly different experimental scheme was used in thermographic studies in the range 8–12 μm, which were performed directly during the experiments of LD pumping of active elements with different cooling systems. When the cooling system remained open to the crystal side irradiated with the pumping radiation, we

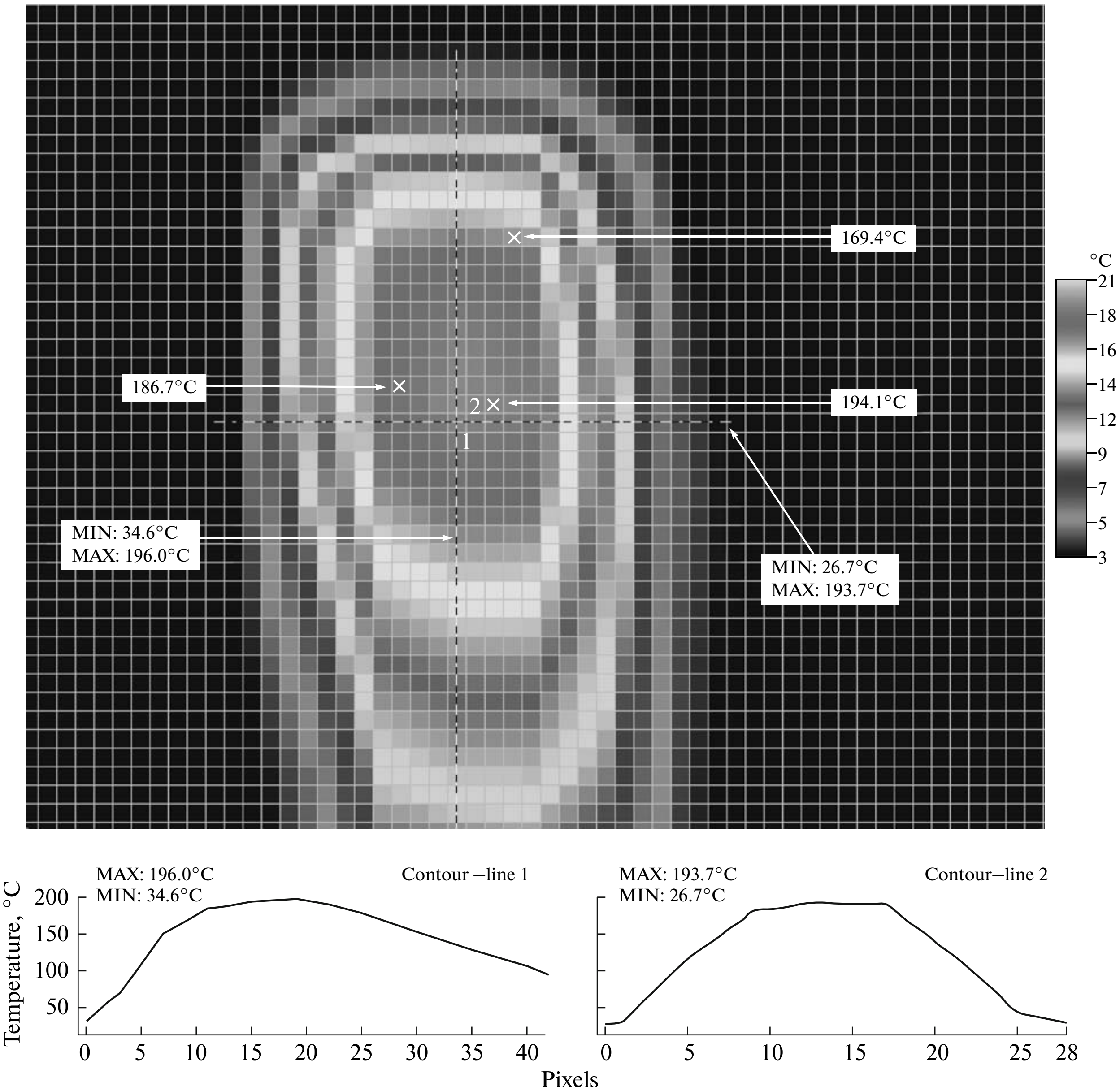

Fig. 4. Temperature distributions in YAG:Er^{3+} laser crystals irradiated with pumping DL radiation.

could record thermograms of two sample planes (positions *a* and *b*). If the cooling system covered both planes of the crystal (in this case, pumping is usually performed through a sapphire plate opaque in the range 8–12 μm), radiation was detected only from the "working" crystal surface (position *b*).

EXPERIMENTAL RESULTS

First, let us consider the experimental results obtained with instruments operating at wavelengths of 8–14 μm.

Figures 2 and 3 show thermograms for YAG:Er^{3+} crystals at different pumping-power levels measured in geometries *a* and *b*, respectively. The laser crystals were attached to radiators cooled with flowing water. As is seen, the regions of elevated temperature appearing in crystals as a result of their irradiation with the diode array are properly visualized with the applied IR imaging instruments (NEC TH-9100 and TH-7800 IR imagers). The temperatures at individual points (e.g., the maximum and minimum temperatures in the lasing region are presented in Figs. 2 and 3) can be measured directly during measurement of a thermogram. Figures 2 and 3 show the plots of the temperature distributions in crystals and at cooling radiators (along the profiles marked with dashed–dotted lines

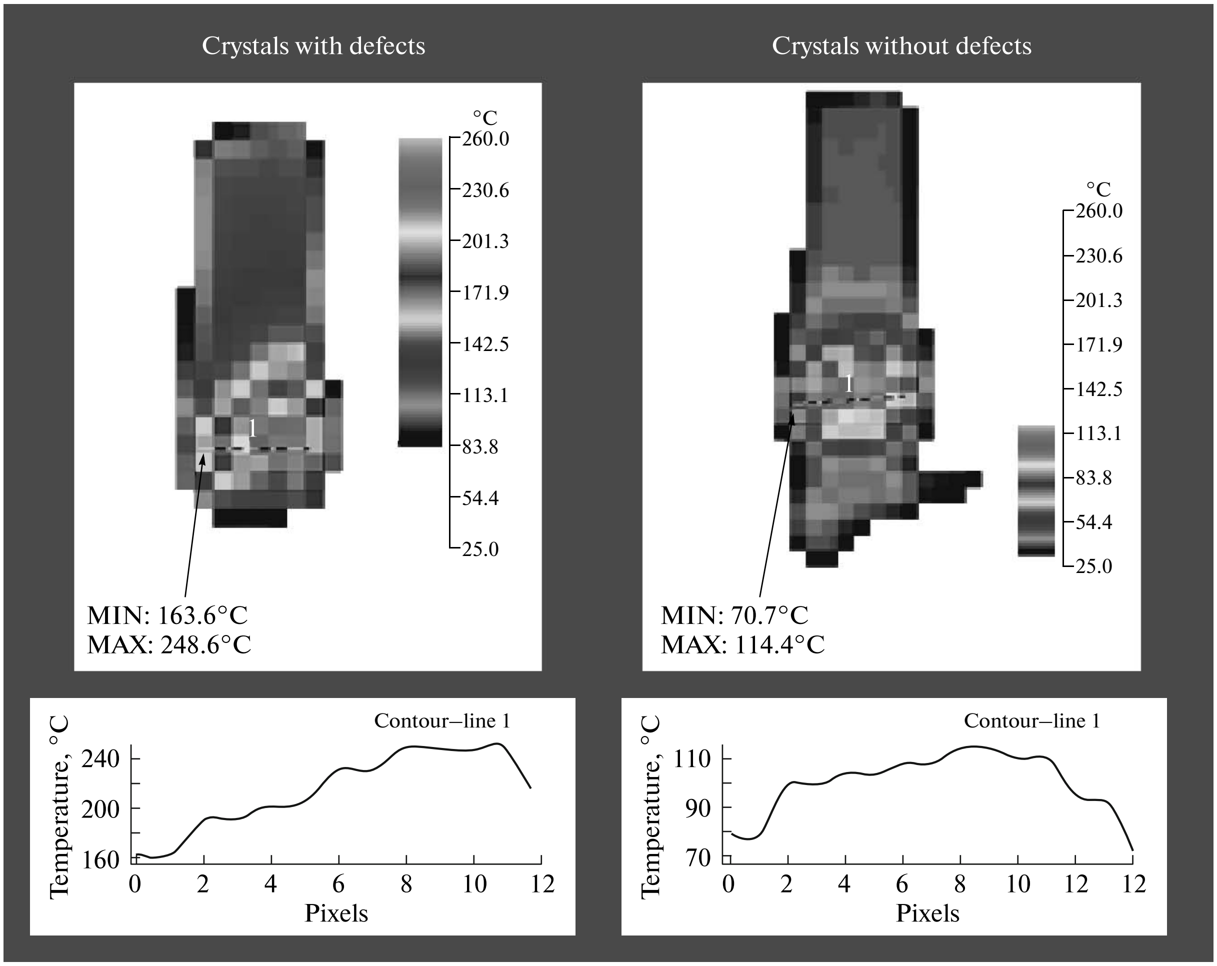

Fig. 5. Thermograms of two YAG:Er^{3+} crystals with different defective structures.

in these figures) and the minimum and maximum temperatures along these profiles.

Figure 4 demonstrate the feasibilities of studying the temperature distribution in laser crystals during their irradiation with pumping radiation. The size of the crystal in Fig. 4 is 10 × 5 × 1 mm. The spatial resolution under the conditions of the performed experiments was low—fractions of a millimeter. However, it can be improved and reach several tens of microns via use of other objective lenses and optimization of the experimental conditions. In this study, we tested the possibility of using infrared imagers for prompt monitoring of the temperature of the lasing region directly in the experimental setup; therefore, no work for increasing the spatial resolution was performed.

As was mentioned above, thermograms and temperature measurements at particular points can be visualized directly during recording. The time necessary for preparing and performing the experiment under actual conditions of laser operation is as long as several minutes. Processing of the obtained results for determining the temperatures in the lasing region and in the crystal regions adjacent to it is performed after an experiment using special programs. The software with which NEC IR imagers are equipped also allows detection of regions with identical temperatures, the maximum, minimum, and average temperatures in selected regions, plotting of the temperature-distribution curves, representation of their 3D images, etc.

Figure 5 shows thermograms for two different YAG:Er^{3+} crystals and demonstrates the feasibilities of the IR imaging technique for detecting crystals containing defects. It is seen that the two YAG:Er^{3+} crystals, which, in the opinion of the manufacturers, were grown under identical conditions and must have the same characteristics, sharply differ in the overheating level under identical pumping-power levels. It is also seen that the region of maximum overheating in the first crystal is shifted from its center to its face. It can be asserted with a high probability that the first crystal contains uncontrollable impurities and defects localized near one of the sample's faces. It is obvious that this crystal is actually unsuitable as a laser element under high-power DL pumping. Thus, the use of the IR imaging technique allows preliminary sorting and

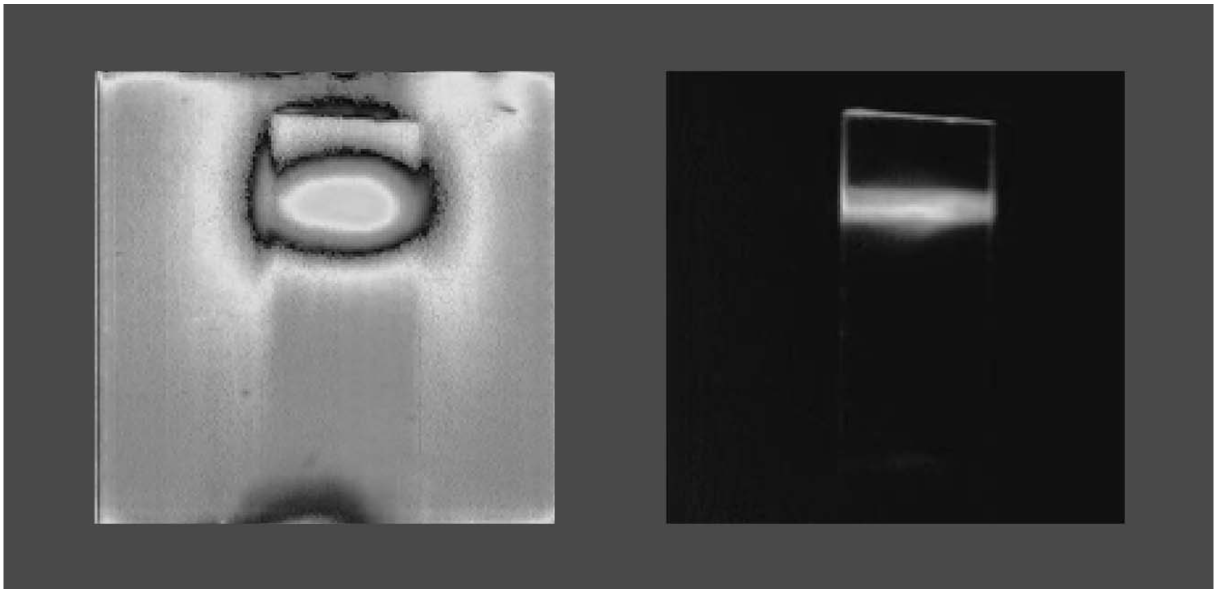

Fig. 6. Thermogram of an YAG:Er^{3+} crystal recorded with the ЛИК-2 IR imager in the range 3–5 μm.

rejection of crystals used as active elements in laser systems with high-power DL pumping.

Let us consider the results obtained in the range 3–5 μm. Figure 6 shows a thermogram of a YAG:Er^{3+} crystal recorded with the ЛИК-2 IR imager. As is seen, the region of elevated temperature appearing under diode pumping is visualized well. The spatial resolution in this scheme was ~0.1 mm^2 (a region detected by a single pixel of the IR imager). In this case, the pattern is formed by combined radiation collected from different regions of the crystal volume. This circumstance and the aforementioned problem of uncertainty of the emissivity for the lasing region considerably complicate the problem of determining the temperature. Taking into account that previous results show the possibility of promptly determining the temperature of the lasing regions adjacent to the crystal surface, it was decided that, within the framework of this study, no detailed investigation would be performed at wavelengths of 3–5 μm. However, this experiment shows the possibility of studying temperature fields over the entire lasing region.

CONCLUSIONS

This study has shown that modern IR imagers operating in the range 8–14 μm can be efficiently used to promptly monitor the near-surface temperatures in the lasing regions of solid-state lasers under high-power coherent pumping. In our opinion, this is a quite reliable method for evaluating the overheating of the entire lasing region, the temperature distribution in it, and the operating efficiency of cooling systems and preliminarily rejecting “defective” crystals. It should be noted that the performance characteristics of uncooled bolometric devices, to the class of which NEC-produced instruments belong, are sufficient for performing such experiments. From the standpoint of the convenience of operation, they have doubtless advantages over cooled IR imagers.

In principle, detailed studies of the temperature fields within the entire lasing region can be performed with devices operating in the range 3–5 μm. However, in this case, it is necessary to solve the problem of measuring the emissivity and separating thermal radiation fluxes emitted from different regions of the crystal overlapping one another.

REFERENCES

1. Chizhikov, V.I., *Soros. Obrazov. Zh.*, 2001, no. 8, p. 103.
2. Frede, M., Wilhelm, R., and Kracht, D., *Opt. Lett.*, 2006, vol. 31, no. 24, p. 3618.
3. Rogal’skii, A., *Infrakrasnye detektory* (Infrared Detectors), Novosibirsk: Nauka, 2003.
4. *Trudy IOFAN* (Proc. of General Phys. Inst., Russ. Academy of Sciences), Moscow: Nauka, 1989, vol. 19, p. 3.