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RESEARCH ARTICLE

Thermal conductivity of doped YAG and GGG laser crystal

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Abstract To study the thermal conduction characteristics of different doped YAG and GGG laser crystals, the thermal conductivity of different doped YAG and GGG laser crystals generated at 273–393 K were measured by making use of instantaneous measurement method. The temperature field model of the experimental sample was established and the function of thermal conductivity to temperature was educed. The obtained conductivity to temperature curves almost conformed to the experimental results. The experimental results show that the thermal conductivity of the laser crystal decline with temperature, the thermal conductivity of YAG laser crystal declines when adding Yb ions, and the thermal conductivity of the GGG laser crystal declines with the rising of the doped Nd ions concentration. Finally, the experimental results were theoretically explained.

Keywords materials, thermal conductivity, measurement study, laser crystal

1 Introduction

Up to now, doped YAG crystal is still the most popular crystal material used in solid-state lasers in the field of machining industrial materials and martial application. Recently, the GGG series of crystals have received lots of attention. Being the same as YAG crystal, $Gd_3Ga_5O_{12}$ (GGG) and $Gd_3Sc_2Ga_3O_{12}$ (GSGG) crystals are the important laser materials [1]. Refs. [2,3] reported the performance of Yb:YAG and Nd:GGG lasers and Ref. [4] reported the disfigurement of Nd:GGG laser crystal. Thermal conductivity is an important physical characteristic of crystals in view of their particular usage. Because the measurement of thermal conductivity is relatively difficult, it has become a main research direction. The means of measuring the thermal conductivity of solid materials can be divided into certain and uncertain state method. The instantaneous measurement method has the advantage of low effect, good precision, high repetition and so on. Ref. [5] reported the thermal conductivity of YAG and GGG at 1–300 K. We measured the thermal conductivity rate κ of different doped synthetic garnet laser crystals at 273–393 K, analyzed theoretically and explained the experimental results via simulating the temperature field, solid theory and microcosmic mechanism of heat exchange.

2 Experimental principle

The physical property measurement system (PPMS), made by Quantum Design Corporation of the USA, was used for measuring thermal conductivity. The samples were cut from the as-grown crystals and polished into a dimension of 10 mm × 4 mm × 2.5 mm to meet the demand of the measurement apparatus. Both ends of the sample were agglutinated by copper strip electrodes with epoxy. The electrodes were connected to a heater shoe and thermometers. Heaters were run with impulse heat, the persistent time was 6 min, and interval time was 8 s. The temperature of the sample increased continuously at a rate of 0.75 K/min during the measurement. The measurement time of one sample was about 3 h.

The measurement principle is shown in Fig. 1. The system heated end 1 by choosing the seemly impulse power and width, controlled the temperature of end 3, and measured the temperature of ends 2 and 4. We calculated the heat exchange function by the equations of heat flux and the value of the thermometer, and then derived the curve of temperature change.

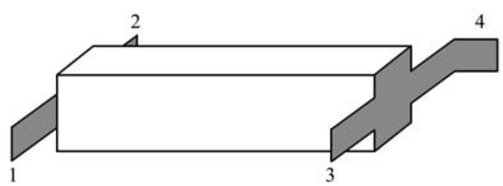

Fig. 1 Structure of two lines attachment

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We founded the academic model based on the measurement theory which is shown in Fig. 2. T_h and T_c are the heating and cooling temperatures, respectively, T_l and T_r are the temperature of left and right end of the sample, respectively, P_1 is the heating power, P_2 is the cooling power, P is the flow power through the sample. We can get the differential equation [6] of the heat exchange and boundary qualifications based on the academic model:

$$\begin{cases} \frac{\partial}{\partial t}(\rho c T) = \nabla(\kappa \nabla T) + q_v, \\ T = T_l, \quad q_v = \frac{P_1 - K_1(T_l - T_h)}{A} \quad (x=0), \\ T = T_r, \quad q_v = \frac{P_2 - K_2(T_r - T_c)}{A} \quad (x=l), \end{cases} \tag{1}$$

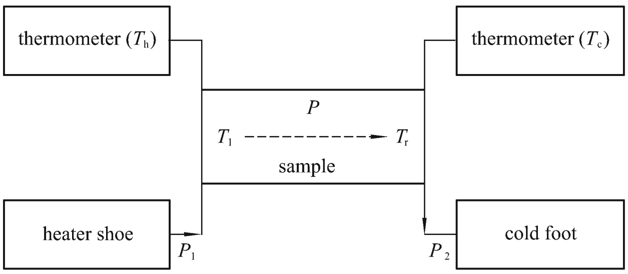

Fig. 2 Sketch map of the model

where ρ is the density of the material, c is specific heat, κ is thermal conductivity rate, q_v is quantity of heat unit volume; l is the length of the sample, A is cross-area, K_1 and K_2 are the heat exchange of two ending electrodes respectively. The temperature of the sample changes a little during the measurement, and the quadratic differential coefficient of temperature was considered as zero; the effect of $\mathrm{d}T_h/\mathrm{d}t$ and $\mathrm{d}T_c/\mathrm{d}t$ were omitted. The temperature difference of two ends is

$$\Delta T = T_h - T_c + \Delta T_1 - \Delta T_2 + \exp\left(\frac{-t}{\tau_1}\right) - \exp\left(\frac{-t}{\tau_2}\right), \tag{2}$$

where $\Delta T_1 = P_1/K_1$, $\Delta T_2 = P_2/K_2$, $\tau_1 = A\rho c/K_1$, $\tau_2 = A\rho c/K_2$. ΔT is the function of t, the other quantity is known. Heat exchange $K = P/\Delta T$, P was replaced by P_1, then

$$K = (P_1 - P_{\text{radiate}})/\Delta T, \tag{3}$$

the expression of radiation power [7] $P_{\text{radiate}} = \sigma s \varepsilon \times (T_1{}^4 - T_2{}^4)/2$, where $\varepsilon = 0.01$ is the radiation coefficient, s is the surface area, σ is Stefan-Boltzmann coefficient, T_1 and T_2 are the sample's average temperature and environment temperature. Thermal conductivity of the sample could be derived via the formula $\kappa = Kl/A$.

3 Experimental results

The thermal conductivities of different doped YAG and GGG laser crystals were determined experimentally in our experiments. The measurement results and standard deviation are shown in Fig. 3. The biggest standard deviation was 0.17976, the accuracy of the experimental apparatus was 5%. The calculated curves of the academic model are shown in Fig. 4.

4 Experimental analyses

The experimental measurement curves combined with the academic calculation are shown in Figs. 3 and 4. The contrast of measurement to reference is listed in Table 1, and atomicity fraction adulteration inverse proportion.

It was notable that κ value of laser crystals decrease as the temperature increase as shown in Figs. 3 and 4. Since the crystals studied here are all nonmetallic and there are no free electrons to carry the heat, the heat transport depends predominantly on the phonons. The theoretical expression of the thermal conductivity is

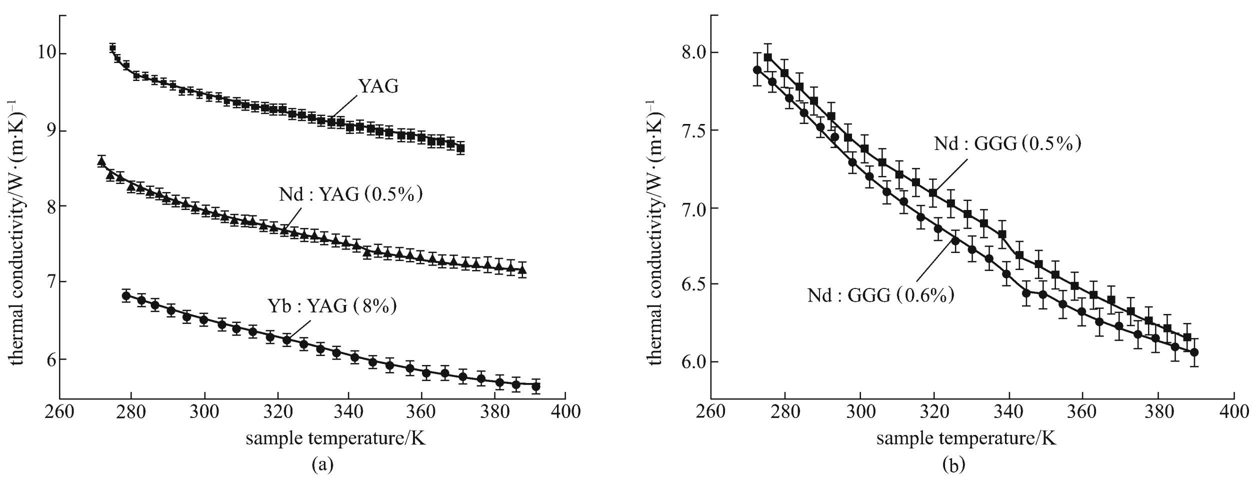

Fig. 3 Thermal conductivity of laser crystal of experimental results. (a) YAG, Yb:YAG and Nd:YAG; (b) Nd:GGG

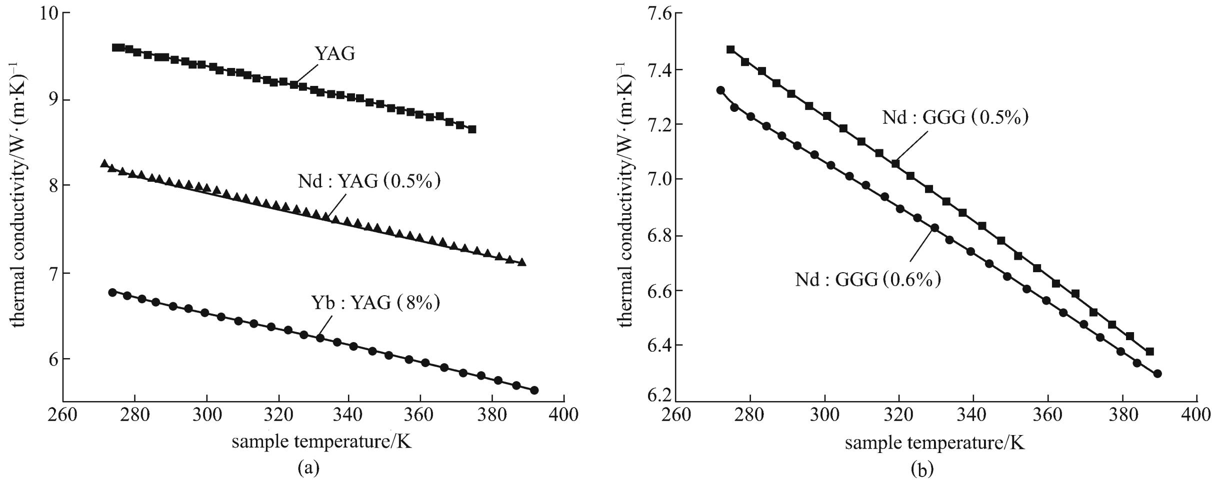

Fig. 4 Thermal conductivity of laser crystal of theoretic results. (a) YAG, Yb:YAG and Nd:YAG; (b) Nd:GGG

Table 1 Contrast of the experimental results with reported room temperature (300 K)

	YAG	Yb:YAG (8%)	Nd:YAG (0.5%)	Nd:GGG (0.5%)	Nd:GGG (0.6%)
thermal conductivity/W·(m·K)$^{-1}$	9.48	6.52	7.94	7.24	5.82
value of references (dopant atomicity faction)/ W·(m·K)$^{-1}$	10.3 [8]	7 [9] (8%)	13 [10] (1.1%)	9 [11] (>2%)	9 [11] (>2%)

$$\kappa = \frac{1}{3} c_V \lambda \bar{v}, \tag{4}$$

where c_V is the constant volume specific heat, λ is the phonon mean free paths, $\bar{v}$ is the average sound velocity. The dependence of the thermal conductivity rate on the temperatures is mainly affected by phonon mean free paths. Generally, the mean free paths of phonons have mainly two different dependences on the temperature:

$$\lambda \propto e^{\Theta_D/(aT)} \ (T \ll \Theta_D), \tag{5}$$

$$\lambda \propto \frac{1}{T} \ (T \gg \Theta_D), \tag{6}$$

where Θ_D is the Debye temperature, a is a constant between 2 and 3, and T is absolute temperature. Since temperatures measured in our work were much lower than the Debye temperatures reported, the change tendency of the mean free paths of phonon should be ascribed to Eq. (5). Because the temperatures are attributed to higher temperature range, the κ value of laser crystals decrease with the temperature.

It can be seen that the κ value of YAG crystals reduced a lot after doping with Nd^{3+} and Yb^{3+} in Fig. 3(a) and Fig. 4(a). Doped $Nd^{3+}$and Yb^{3+} replace the site of Y^{3+} of YAG crystals. The atomic weight of Yb^{3+}, Nd^{3+} and Y^{3+} are 173.04, 144.24 and 88.91, the ion radius of Yb^{3+}, Nd^{3+} and Y^{3+} are 0.086, 0.1 and 0.089 nm. The atomic weight of Yb and Nd are bigger than Y's, the ion radius of Yb^{3+} is smaller than Y^{3+}'s, and the ion radius of Nb^{3+} is bigger than Y^{3+}'s. As the YAG crystal doped with Yb^{3+} made the density increase around the doped ions, uniformity degree of point quality declined, ordering degree declined, and the thermal conductivity declined. After the YAG crystal was doped with Yb^{3+}, the atomic weight of Nd became bigger than Y and the ion radius of Nb^{3+} became bigger than Y^{3+}'s. The two changes made the density increase around the doped ions take on the opposite direction, and the thermal conductivity declined, which is similar to the experimental result.

As shown in Fig. 3(b) and Fig. 4(b), the κ value of 0.6% doped Nd:GGG is smaller than the 0.5% doped. Nd^{3+} replaces the site of Gd^{3+} of GGG crystals, the atomic weight of Nd and Gd are 144.24 and 157.25, respectively. The ion radius of Nd^{3+} and Gd^{3+} are 0.1 and 0.094 nm; the atomic weight of Nd is smaller than Y's, the ion radius of Nd^{3+} is bigger than Gd^{3+}. The doped Nd^{3+} ions made crystal lattices malformed; the higher the doping, the more malformed the crystal lattices became, which make the κ value of crystals decline.

5 Conclusion

The thermal conductivity of different doped YAG and GGG synthetic garnet laser crystals were measured by instantaneous measurement method at 273–393 K. The experimental results indicate that: thermal conductivity dependence on the temperature follows an exponential change, the κ value of YAG crystals reduced after doping with Yb^{3+}. The κ value of GGG reduced as the doped Nd^{3+} concentration increased. We analyzed the experiment theoretically, established the temperature field model of the experimental sample, and educed the function of thermal conductivity to temperature. The curves of conductivity to temperature obtained almost conformed to the experimental results. The changing trend of the thermal conductivity of YAG and GGG crystals based on temperature are mainly affected by phonon mean free paths. The thermal conductivity decline when adding ions, which is the result of order degree decrease malformed by lattices.

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