

Laser ceramic. 2. Spectroscopic and lasing properties

S. G. Garanin and N. N. Rukavishnikov

*Russian Federal Nuclear Center—All-Russia Scientific-Research Institute of Experimental Physics,
Institute of Laser-Physics Research, Sarov*

A. V. Dmitryuk^{a)} and A. A. Zhilin

Scientific and Technological Institute of Optical Material Science, VNTs S. I. Vavilov State Optical Institute, St. Petersburg

M. D. Mikhaïlov

St. Petersburg State Polytechnic University, St. Petersburg

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This section of the review discusses the main features of the construction of laser ceramic and how they affect the spectroscopic and lasing properties of the new material. The technology for obtaining a laser ceramic affects the processes that cause the ions of the rare-earth elements to be segregated and, as a consequence, affects their spectroscopic properties. © 2011 Optical Society of America.

INTRODUCTION

The fundamental difference of laser ceramic from other active media of solid-state lasers (laser glasses, crystals) is that this material includes a large number of defects, such as excess pores and boundaries of microcrystalline grains. The indicated defects determine how the lasing and spectroscopic properties of laser ceramic differ from the properties of single crystals of the same composition.

It is obvious that the nature of the indicated defects of laser ceramic and the possibility of removing them are fundamentally different. Actually, pores are a technological defect and can in principle be eliminated or their number minimized by means of various technological methods and approaches.

At the same time, the main difference of laser ceramic from other optical materials is the presence of boundaries between the randomly oriented microcrystalline grains. Depending on the technology used to fabricate them, the typical size of the microcrystals in a laser ceramic varies from several micrometers to tens of micrometers. It is obvious that the role of the interphase boundary in forming the spectroscopic characteristics of the dopant increases as the size of the microcrystals decreases.

HOW PORES AND INTERPHASE BOUNDARIES AFFECT THE SPECTROSCOPIC AND LASING PROPERTIES OF A LASER CERAMIC

Questions associated with the methods of obtaining laser ceramic and processes for reducing the pore concentration are considered in detail in the first part of this review.¹ In this section, we consider how the pores affect the lasing properties of a laser ceramic.

Reference 2 reported a quantitative study of how residual pores affect the optical losses and lasing properties of Nd:YAG

laser ceramic when it is pumped with a semiconductor laser. Based on direct lasing experiments, it has been convincingly shown that the main cause of the variation of such lasing characteristics of a laser ceramic as the lasing threshold and the differential coefficient of efficiency¹⁾ is the number (or volume fraction) of pores in the ceramic. The mean pore size in the indicated experiments was monitored and equalled several micrometers in diameter. The influence of the volume fraction of pores on the lasing characteristics is illustrated in Fig. 1.

It follows from the data shown in Fig. 1 that, as the pore concentration in ceramic samples decreases, their lasing characteristics approach those of single crystals. Let us consider these results in more detail.

In ceramic samples with a volume pore concentration of 120 ppm, the slope efficiency somewhat exceeds the analogous characteristic of single crystals (30.6% and 25.9%, respectively). However, this effect is explained by the trivial difference in the dopant (neodymium) concentration. In the studies of samples in Ref. 2, the neodymium concentration was 0.9 at.% for the single crystal and 1.1 at.% for the laser ceramic. Therefore, the absorption coefficient of the pump radiation in the neodymium absorption band was higher in the ceramic samples than in the single crystals.

Much more important for understanding the specific features of laser ceramic are the differences in the lasing thresholds. The laser threshold was 61 mW for single-crystal Nd:YAG, while it was 97 mW for a ceramic sample with the minimum pore concentration. The increase of the lasing threshold means that the test samples of laser ceramic have loss channels of the pump radiation in addition to those in single crystals.

Three loss channels are possible in principle: Radiation scattering at the lasing wavelength, inactive absorption of stimulated emission by uncontrolled impurities, and losses

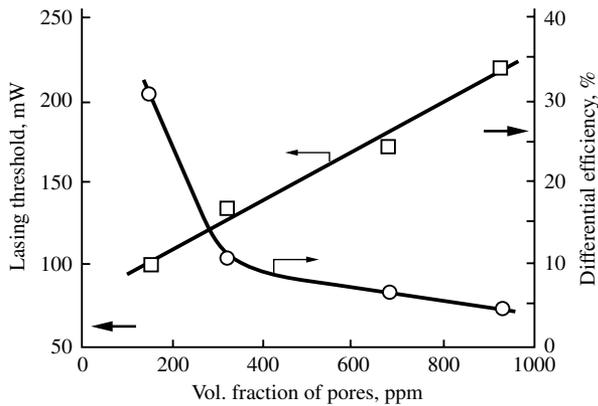


FIG. 1. Lasing characteristics of Nd:YAG ceramic (lasing threshold and slope efficiency) vs volume concentration of pores.²

caused by quenching of the dopant luminescence. According to the data of Ref. 2, the losses to light scattering in the samples being compared are identical and are caused only by the presence of excess pores. Taking into account the high degree of purity of the reagents used in the experiments described here, the assumption of large inactive absorption in the laser ceramic by comparison with the crystals also seems very unlikely.

Thus, the most probable cause of the relatively high lasing threshold in laser ceramic can be the smaller quantum yield of luminescence due to concentration quenching of the neodymium luminescence. Since the dopant concentration is similar in the ceramic and the single crystals (1.1 and 0.9 at.%, respectively), to explain the results of Ref. 2, it should be assumed that the dopant distribution in the ceramic must be nonrandom; i.e., dopant-segregation processes must occur in the ceramic test samples.

It should be emphasized that the influence of dopant segregation is characteristic of solid-state laser media and plays an extremely important role in processes of nonradiative energy transport of electron excitation, determining in the last analysis the spectroscopic and lasing characteristics of the material.^{3,4}

Actually, when the dopant distribution is nonuniform in the volume of the laser material, the actual distances R between the dopant ions differ from the mean statistical values. At the same time, the probability W of an elementary event of nonradiative energy transport as a result of inductive-resonance interactions is determined by the actual distances between the interacting particles. The dependence of the probability of nonradiative energy transport on the distance between the interacting particles is exceedingly strong. For pairwise interactions, $W \sim R^{-6} - R^{-10}$, depending on the multipole nature of the interaction.⁵ Therefore, even insignificant deviations of the local dopant concentration from the mean statistical value can substantially change the quenching efficiency of the dopant luminescence in the case of cross-relaxation quenching, which occurs for neodymium. Let us consider the possible prerequisites for segregation processes in the ceramic.

As already pointed out, the main difference of laser ceramic from other optical materials is the presence of boundaries between the randomly oriented microcrystalline

grains. Typical sizes of the microcrystals in laser ceramic vary from several micrometers to tens of micrometers, depending on the technology used for fabrication. It is obvious that the role of the interphase boundary in forming the spectroscopic characteristics of the dopant increases as the size of the microcrystals decreases.

It is obvious that the influence of the boundary layer on the spectroscopic and lasing properties of laser ceramic needs to be taken into account. At the same time, despite the numerous studies of this problem, there is currently no unified viewpoint on the role of the interphase boundary or on segregation processes in laser ceramic, and the experimental data on this question are rather contradictory. Because of the importance of the problem under consideration, we shall dwell on this in detail.

The object of most of the studies is Nd:YAG, which is the most widespread and important laser ceramic for practical applications. For neodymium-doped media, unlike ytterbium-doped media, segregation plays a substantially greater role in forming the spectroscopic and laser characteristics of the ceramic because of the features of the energy-level diagram of the dopant (neodymium). In fact, the level diagram of neodymium assumes that concentration quenching of luminescence is possible according to a cross-relaxation scheme.⁶⁻⁸ Depending on the dopant concentration, luminescence quenching occurs either as a result of direct static interaction, or in a regime controlled by the diffusion of electronic excitation in an energy-donor system. The luminescence quenching is accompanied by a change of its quenching kinetics. In general, the luminescence-quenching kinetics of neodymium are described by the complex function⁶⁻⁸

$$I(t) = I_0 \exp(-t/\tau_0 - P(t)) \quad (1)$$

where

$$P(t) = \gamma t^{1/2} + Wt, \quad (2)$$

$I(t)$ is the luminescence intensity at time t , I_0 is the luminescence intensity at the end of the short exciting pulse, τ_0 is the radiation lifetime of the excited state, and γ and W are constants for a fixed dopant concentration. The γ and W parameters depend on the dopant concentration and can be used as indicators of the segregation processes.^{6,8}

The luminescence-quenching kinetics of neodymium as a function of the dopant concentration in Nd:YAG laser ceramic as the neodymium concentration varies within wide limits are studied in detail in Refs. 7 and 8. Based on kinetic studies, Refs. 7,9 and 10 conclude that there is no dopant segregation. At the same time, Merkle *et al.*⁸ arrive at the opposite conclusions relative to segregation processes in the ceramic of interest and assert that the dopant distribution at high concentrations differs from a random distribution.

In connection with the obvious contradictions in interpreting the data from the study of the spectroscopic characteristics of Nd:YAG laser ceramic, the results of studies of the dopant distribution should be analyzed by "direct" methods. Such studies are reported in Refs. 11 and 12.

TABLE 1. Distribution of the composition of laser ceramic over the cross section of the sample.¹¹

Component	Conc., mass%	
	Grain boundary	Inside grain
Al ₂ O ₃	33.6	41.1
Y ₂ O ₃	58.1	58
Nd ₂ O ₃	3.2	0.9
SiO ₂	5.1	Below detection threshold

The influence of various process regimes on the optical properties of transparent laser ceramics synthesized from the oxides Al₂O₃, Y₂O₃, and Nd₂O₃ by the method of solid-phase sintering is studied in these papers. Silicon oxide SiO₂ was used as an additive to improve the sinterability and suppress grain growth and was introduced into the initial mix in the form of tetraethoxysilane (TEOS). The TEOS concentration was varied from 0.1 to 1.0 mass%. The methods of scanning electron microscopy and X-ray spectral microanalysis were used to determine the elementary composition of the ceramic grains and the grain interfaces.

The results of X-ray microanalysis of samples with a high TEOS concentration (1 mass%), from the data of Ref. 11, are presented in Table 1. It can be seen that, in ceramic samples, the dopant (neodymium) distribution over the sample volume is substantially nonuniform. The neodymium concentration is a factor of 3.5 greater at the grain boundary than in the bulk. Moreover, the calculated dopant concentration in the test samples is 1.1 mass%, whereas the neodymium concentration in the main phase of the ceramic (the grains) is equal to 0.9 mass% according to the X-ray-analysis data. This means that approximately 20% of the overall dopant (neodymium) concentration is concentrated on the grain boundaries. The composition of the boundary phase substantially differs from the composition of the grains.

At the same time, it must be pointed out that, in Ref. 12, the same authors, using the same research methods, obtained fundamentally different results on the neodymium distribution in the volume of the laser ceramic. Data are given in Table 2 on the elementary composition of the grains and the boundary region of the samples studied in Ref. 12. It should be pointed out that TEOS was also used in Ref. 12 as a component to catalyze sintering, but in a concentration of 0.3 mass%. The neodymium oxide concentration as synthesized was 2.4 mass%.

As follows from the data of Table 2, the neodymium distribution over the volume of the ceramic in the samples studied in Ref. 12 is uniform within the limits of measurement error. The absence of data on the SiO₂ concentration is explained by the small amount of this process mix.

A comparison of the data given in Tables 1 and 2 shows that segregation processes in the laser ceramic strongly depend on the process for obtaining the ceramic—in particular, on the concentration of SiO₂ additive in the composition of the mix. The latter circumstance until the present has received insufficient attention.

The authors of Refs. 13–15 arrive at the same contradictory results relative to the neodymium distribution in the laser ceramic, using the method of confocal microscopy in combination with luminescence and Raman spectroscopy to

TABLE 2. Analysis of the composition of grains and grain boundaries of YAG ceramic with neodymium concentration 2.4 mass%.¹²

Number of measurement point	Concentration, mass %		
	Al ₃ O ₃	Y ₂ O ₃	Nd ₂ O ₃
Grain			
1	42.49	55.21	2.3
2	42.5	55.19	2.31
3	42.53	55.08	2.39
4	42.51	55.25	2.24
5	42.5	55.19	2.31
Grain boundary			
6	42.57	54.98	2.45
7	42.55	55.01	2.44
8	42.49	55.21	2.3
9	42.55	55.04	2.41
10	42.52	55.15	2.33

study this problem. The technique that they used allowed them to obtain two- and three-dimensional luminescence images of microregions of the ceramic with submicron resolution.

The spatial distribution of the neodymium luminescence and the Raman spectra in ceramic samples of Nd:YAG with a dopant concentration of 5 at.% was investigated in Ref. 13. As a binding component, 0.5 mass% of TEOS was introduced into the mix. The spectra were scanned both inside the grains and on their boundaries. No substantial changes were detected in the shape of the luminescence and Raman spectra, and this served as a basis for concluding that the composition of the ceramic was uniform both in the bulk and at the grain boundaries.

Note that a technique based only on an analysis of the shape of the luminescence spectrum cannot serve as a basis for concluding that there is no dopant segregation, because the luminescence of the rare-earth (RE) ions is not very sensitive to insignificant changes of the surroundings of the dopant. A more sensitive tool in studying segregation processes is to determine the parameters of the concentration quenching of the luminescence.

Unlike Ref. 13, significant attention was paid to the variation of the luminescence intensity over the cross section of the sample in Refs. 14 and 15. As a result of a detailed analysis of the experimental data, the authors concluded that there was an inhomogeneous distribution of dopant over the volume of the ceramic. The neodymium concentration at the boundary of the grains exceeds the bulk concentration. The increase of the dopant concentration reduces the intensity of the neodymium luminescence at the grain boundary because of concentration quenching of the dopant luminescence.

Summarizing the results of the papers devoted to the study of the dopant distribution over the volume of a ceramic, it should be pointed out that RE-segregation processes at the grain boundary sometimes play a substantial role in forming the spectroscopic and laser characteristics of a laser ceramic. These processes play a special role in the case of a neodymium-doped ceramic because of the cross-relaxation scheme of concentration quenching of the luminescence. The contribution of segregation processes to concentration quenching of the luminescence strongly depends on the process for obtaining the ceramic—in particular, on the temperature–time sintering regimes, the use of binding additives, and the dopant concentration. Ignoring the technological features of obtaining

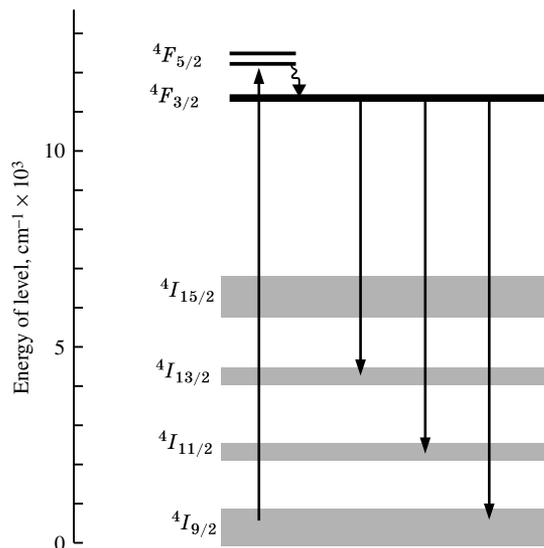


FIG. 2. Generalized energy-level diagram of Nd^{3+} in the Nd:YAG crystal. The arrows show the most important transitions.²⁰

a laser ceramic can cause inaccurate conclusions concerning the lasing possibilities of a new laser material.

At the same time, despite the possibility of segregation processes, the spectroscopic properties of a laser ceramic doped with RE ions are close to the properties of analogous single crystals. This trait of laser ceramic is pointed out in many papers devoted to a comparative analysis of the properties of laser ceramic and single crystals.^{16–20} The similarity of the spectroscopic properties of RE dopants in single crystals and ceramic can be explained by the fact that the relative fraction of dopant ions concentrated on the interface of the grains is small with respect to the bulk concentration of the dopant. Moreover, local variation of the RE-ion concentration weakly affects the position of the spectral lines and stimulated-transition cross sections because the electronic $4f$ shell is screened by the outer electron shells.

The similarity of the spectroscopic properties of dopants in crystals and laser ceramic of the same composition makes it possible to use numerous experimental and theoretical data on the properties of laser crystals, contained in monographs and reviews,^{3,21,22} to predict the properties of a laser ceramic.

THE SPECTROSCOPIC AND LASER PROPERTIES OF AN OXIDE CERAMIC DOPED WITH NEODYMIUM OR YTTERBIUM

The most widespread type of laser ceramic is currently Nd:YAG. At the same time, the modern development trend for solid-state lasers with semiconductor pumping is to use ytterbium-doped crystals and ceramic as the active medium—in particular, the laser ceramic Yb:YAG. Let us consider the spectroscopic properties of the indicated materials in more detail.

Figure 2 shows a segment of the energy-level diagram of Nd^{3+} in a laser ceramic to illustrate possible lasing diagrams of neodymium with selective pumping by semiconductor lasers.

A four-level lasing diagram of Nd^{3+} is traditionally used in most applications, for which pumping with a radiation wavelength of 808 nm is done in an absorption band of

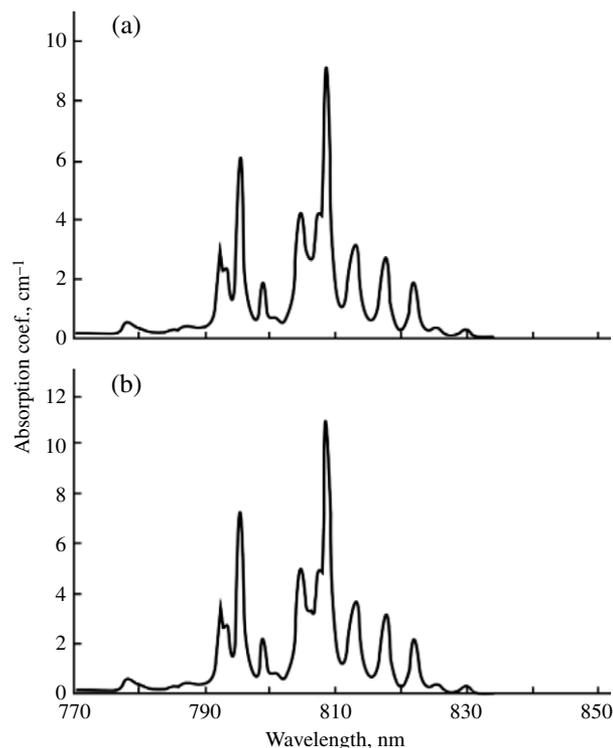


FIG. 3. Segments of the absorption spectra of single-crystal Nd:YAG (a) and ceramic Nd:YAG (b). Dopant concentration 0.9 mol% in the crystal and 1.0 mol% in the ceramic.¹⁶

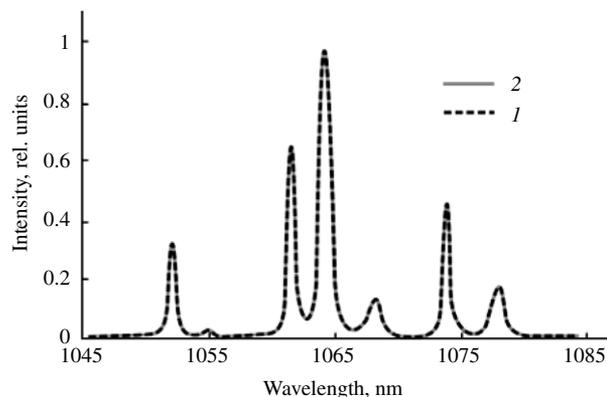


FIG. 4. Segment of the luminescence spectra of single-crystal Nd:YAG (1) and ceramic Nd:YAG (2). Dopant concentration 0.9 mol% in the crystal and 1.0 mol% in the ceramic.¹⁶

Nd^{3+} (${}^4I_{9/2} \rightarrow {}^4F_{5/2}$). The absorption spectra of laser-ceramic and single-crystal Nd:YAG are shown in Fig. 3.

The metastable $\text{Nd}^{3+}({}^4F_{3/2})$ state is excited as a result of nonradiative relaxation. Stimulated emission can be generated in several channels, but the line with wavelength 1.064 μm (see Fig. 4) possesses the largest stimulated-transition cross section.

It is obvious from the four-level diagram of neodymium lasing that a significant part of the excitation energy is dissipated in heating the medium, since the difference between the radiation frequencies of the pumping and lasing is about 3000 cm^{-1} , or 24% of the frequency of the pump radiation. Thermal effects caused by the significant Stokes shift of the luminescence limit the possibilities of increasing the power

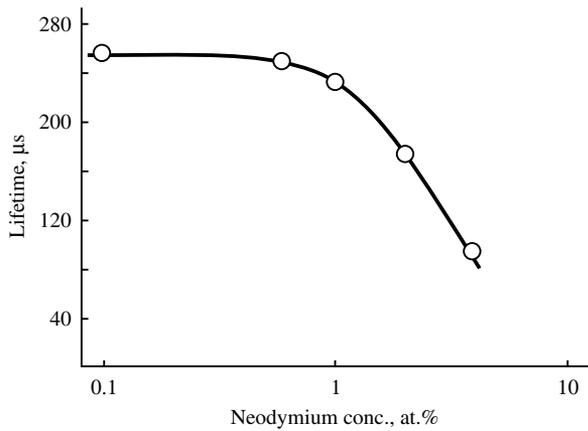


FIG. 5. Excited-state lifetime vs dopant (neodymium) concentration in the laser ceramic Nd:YAG.¹⁶

of neodymium lasers that operate according to a four-level lasing diagram. Therefore, the possibility of obtaining efficient neodymium lasing in Nd:YAG laser ceramic according to a three-level lasing diagram has been analyzed in a number of papers in recent years.^{23–26}

The three-level lasing diagram of neodymium is implemented with selective pumping in the absorption band of Nd^{3+} ($^4I_{9/2} \rightarrow ^4F_{3/2}$) (see Fig. 2). It is obvious that the quantum defect is substantially less with such a method of exciting neodymium luminescence than with the four-level lasing diagram. The frequency difference of the exciting radiation and the lasing is about 2100 cm^{-1} , with lasing at a wavelength of $1.064 \mu\text{m}$. At the same time, achieving an effective three-level lasing diagram in the ceramic of interest is quite difficult because of the relatively small absorption coefficient at the frequency of the pump radiation.

According to Ref. 20, the absorption coefficient of neodymium for a concentration of 1.0 at.% in Nd:YAG crystals for pump radiation with wavelength 808.4 and 868.4 nm is 9.1 and 2.4 cm^{-1} , respectively. Therefore, crystals and ceramic with a high dopant (neodymium) concentration must be used to increase the efficiency of using pump radiation with a wavelength of 868 nm. At the same time, increasing the neodymium concentration above 1.0 at.% results in pronounced concentration quenching of the luminescence, which is accompanied by shortening of the excited-state lifetime (see Fig. 5). The concentration quenching of the dopant luminescence largely levels out the advantages of the three-level lasing diagram of neodymium.

It is possible to fundamentally reduce the heat evolved in the amplifying medium and consequently to increase the output power of the radiation by using not neodymium but ytterbium as a dopant.

With respect to other trivalent RE ions, Yb^{3+} possesses a unique level diagram, which makes its spectroscopic properties excellent for laser applications. The ytterbium level diagram, besides the $\text{Yb}^{3+}(^2F_{7/2})$ ground state, has a unique excited level $\text{Yb}^{3+}(^2F_{5/2})$ that differs from the ground state by about $10\,300 \text{ cm}^{-1}$ (see Fig. 6).

The large energy gap between the ground state and the excited state and the absence of intermediate energy levels virtually exclude the possibility of not only concentration

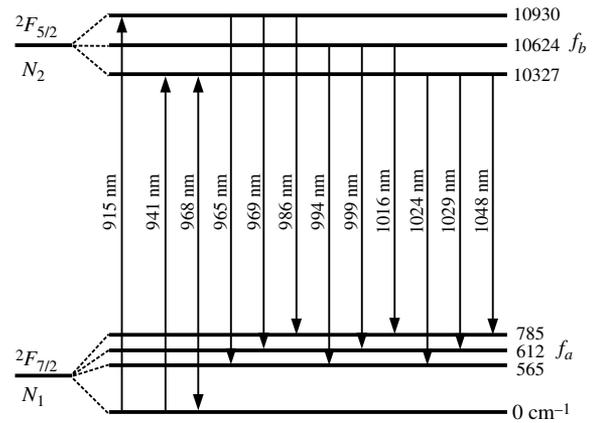


FIG. 6. Energy-level diagram of Yb^{3+} in the Yb:YAG crystal. The arrows show the transitions between the levels.²⁰

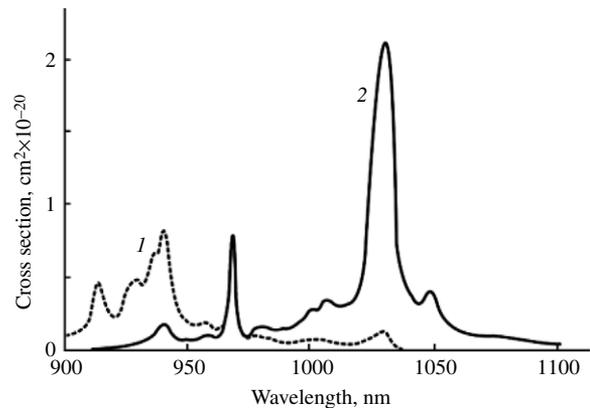


FIG. 7. Absorption (1) and luminescence (2) spectra of Yb^{3+} at room temperature in an Yb:YAG crystal.²⁰

quenching of luminescence but also multiphonon nonradiative relaxation. There is no concentration quenching in Yb:YAG crystals all the way to a concentration of 20 at.%.²⁷

Moreover, the fact that ytterbium has no energy levels in the visible region means that, in the wavelength region close to the lasing wavelength, there can be no photoinduced absorption processes from the excited state and no cooperative processes that result in energy losses of electronic excitation by an up-conversion scheme.

Lasing can be obtained in media doped with Yb^{3+} , because the degeneracy of the $\text{Yb}^{3+}(^2F_{7/2})$ ground state and the $\text{Yb}^{3+}(^2F_{5/2})$ excited state is completely removed in the crystal field, and the energy levels split into Stark sublevels—Fig. 6. The maximum Stark splitting in Yb:YAG crystals is about 785 and 600 cm^{-1} for the ground and excited states, respectively. Taking the Stark splitting into account, the Yb^{3+} lasing diagram can be regarded as quasi-four-level at cryogenic temperatures and quasi-three-level at room temperature.

The absorption and luminescence spectra of ytterbium in a YAG crystal at room temperature are shown in Fig. 7.

As can be seen from these data, a feature of ytterbium is that the luminescence is strongly reabsorbed, because the absorption and luminescence spectra overlap. The gain spectrum of ytterbium therefore substantially differs from

TABLE 3. Spectroscopic characteristics of ytterbium and neodymium in YAG crystals.³⁰

Laser material	Yb:YAG	Nd:YAG
Lasing wave length, μm	1.03 1.05	1.064
Half-width of luminescence line, nm	6.3 5.6	0.6
Emission cross section, $\text{cm}^2 \times 10^{-20}$	2.1 0.31	33
Absorption cross ^a section, $\text{cm}^2 \times 10^{-20}$	0.75 0.75	8.6
Lifetime, ms	0.95 0.95	0.23
Saturation energy density, J/cm^2	8.8 30	0.57
Volume concentration for 1% R^{3+} , $\text{cm}^{-3} \times 10^{20}$	1.38 1.38	1.38

Note.

^a The absorption cross section is given for a wavelength of 0.94 μm for Yb:YAG and 0.809 μm for Nd:YAG.

the luminescence spectrum and depends on the degree of inversion—i.e., on the pump power.²⁸ This circumstance must be taken into account when numerically modelling the gain spectrum.

Because of the luminescence reabsorption, lasing in Yb:YAG crystals and laser ceramic is accomplished at room temperature predominantly at wavelengths 1.03 and 1.05 μm . At the same time, the shape of the gain spectrum makes it possible to tune the lasing wavelength within wide limits: from 1.0 to 1.1 μm .²⁹

A characteristic feature of ytterbium-doped crystals and glasses is the small Stokes shift of the luminescence relative to the exciting radiation frequency. For the laser ceramic Yb:YAG, when a semiconductor laser with radiation wavelength 968 nm is used for pumping, the difference in the radiation frequencies of pumping and lasing is about 600 cm^{-1} , which is a factor of 5 less than for Nd:YAG ceramic.

One more substantial advantage of ytterbium-doped media over neodymium active media is the long lifetime and the absence of concentration quenching. In YAG crystals and laser ceramic, the excited-state lifetime of ytterbium is 950 μs , whereas the excited-state lifetime is 230 μs for neodymium, with a dopant concentration of 1.0 at.%.³⁰

For lasing and the amplification of ultrashort laser pulses, an extremely important characteristic that determines the minimum possible pulse width is the width of the luminescence (gain) spectrum. The half-width of the most intense luminescence line of ytterbium, with maximum at a wavelength of 1.03 μm , is about a factor 10 greater than that of the luminescence line of the laser transition with wavelength 1.064 μm for neodymium. The comparative spectroscopic characteristics of ytterbium and neodymium in YAG crystals are shown in more detail in Table 3.

The drawbacks of the ytterbium dopant of the laser medium include the fact that the laser-transition cross section is smaller than that of neodymium. This increases the lasing threshold and makes it necessary to use high-intensity semiconductor lasers.³⁰

Laser ceramic based on yttrium aluminum garnet doped with neodymium and ytterbium is today the only type of commercially available laser ceramic. Commercially perfected technology makes it possible to fabricate laser ceramic of the indicated type in large sizes, all the way to $10 \times 10 \times 1 \text{ cm}$ (Kinoshima, Japan).^{16,31}

At the same time, research and development on creating processes for producing laser ceramic based on other

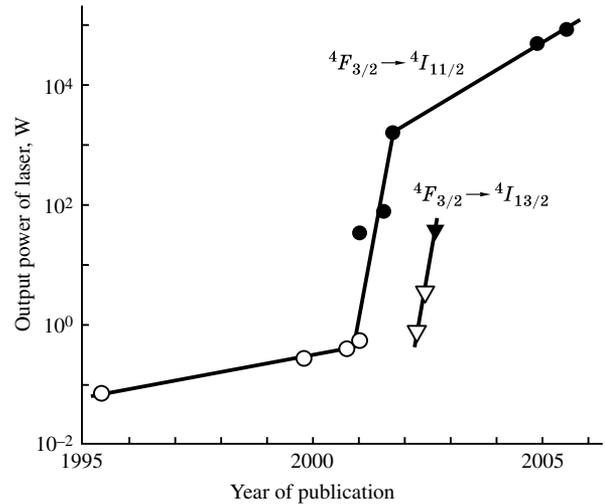


FIG. 8. Dynamics of the power increase of cw lasers based on Nd:YAG ceramic.²¹ The open circles and triangles are for longitudinal pumping, and the closed circles for transverse pumping.

crystalline compounds, mainly doped with neodymium and ytterbium, are being actively pursued worldwide. The results of these studies have been generalized in two reviews.^{10,21}

Lasing of neodymium and ytterbium is currently obtained in laser ceramic with the compositions $\text{Y}_3\text{Al}_5\text{O}_{12}$, $\text{Y}_3\text{Sc}_1\text{Al}_4\text{O}_{12}$, Y_2O_3 , Sc_2O_3 , and Lu_2O_3 . Intensive studies of laser ceramic based on the sesquioxides Y_2O_3 , Sc_2O_3 , and Lu_2O_3 doped with ytterbium are dictated by the circumstance that the gain spectra of ytterbium in these matrices are distinguished by large width by comparison with the spectra of $\text{Y}_3\text{Al}_5\text{O}_{12}$. This makes it possible to create pulsed lasers in the femtosecond region that excel traditional Ti-sapphire lasers in their energy characteristics.

Progress in developing continuous lasers based on laser ceramic is illustrated by the data of Ref. 21, shown in Fig. 8.

The dynamics of the power enhancement of lasers based on laser ceramic staggers imagination. As follows from the data shown in Fig. 8, ever since the first commercial laser ceramic was created in 1995 to the present, the power of ceramic lasers has increased by a factor of 10^6 . Continuous single-channel lasers based on Nd:YAG ceramic are currently the most powerful in the world among solid-state lasers. Their power reaches values of 67 kW, and there is no doubt that the 100-kW line will be exceeded in the near future.

CONCLUSION

In fifty years, ever since the first solid-state laser was created, lasing has been obtained in hundreds of different laser media, including laser crystals and glasses doped with RE ions. However, among all these laser materials, only a few among the collection of their properties have become widely used in practice. This mainly includes laser glasses and crystals of yttrium aluminum garnet doped with neodymium. Each of the indicated high-grade laser materials has its advantages and disadvantages, and therefore they have supplemented but not replaced each other on the market of laser technologies.

In their optical quality, possibilities of fabricating large laser elements with an aperture up to 1 m^2 , and price

characteristics, laser glasses have no competitors among other laser media when powerful and superpowerful pulsed laser systems are being developed in the regime of single laser pulses.

Laser crystals are much superior to laser glasses in their thermophysical characteristics, and this determines their leading role in developments of continuous lasers and pulsed lasers with high pulse-repetition rate. However, existing technologies for growing crystals from the melt have low productivity and do not provide laser elements with an aperture greater than 10^{-2} m². The cost of laser crystals is substantially higher than that of laser glasses.

Laser ceramic is a new class of active laser media, developed in the last 10–15 years. Laser ceramic combines the advantages of both laser crystals and laser glasses in one material. The new material possesses physicochemical and spectroscopic properties identical to those of single crystals of the same composition. At the same time, the technology for producing laser ceramic is substantially more productive and flexible by comparison with the technology for growing single crystals.

Laser ceramic has no fundamental technological limitations for creating active elements with an aperture of 10^{-1} – 1 m². Moreover, the technology for producing laser ceramic makes it possible to create high-temperature laser materials with a melting temperature as high as 2500 °C. This opens up wide possibilities for synthesizing new laser media with improved laser characteristics.

Laser ceramic has already been transformed from a unique object of scientific research into a commercial product with high competitive potential. There is no doubt that, with the further development of a commercial technology for laser ceramic, this material will not only supplement existing active media for solid-state lasers but will also successfully compete with them, especially when developing powerful and superpowerful lasers.

^{a)}Email: alexander.dmitry@mail.ru

¹⁾The term *slope efficiency* is used in the English-language scientific and engineering literature.

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