successful development of laser research in our country. The pioneering experiments performed by S I Vavilov and V L Levshin opened the window onto the world of diverse nonlinear phenomena in optics. Thanks to the application of laser light sources, S I Vavilov's pupils and successors made a major contribution to the discovery and investigation of new nonlinear optical effects. The spirit of devotion to science displayed by S I Vavilov and his personal example of selfless labor under incredibly difficult conditions are still helpful in retaining the high scientific level of optical research in our country.

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PACS numbers: **42.50.–p**, **42.70.–a**, **78.47.–p**
DOI: 10.3367/UFNe.0181.201112j.1334

Luminescent nanophotonics, fluoride laser ceramics, and crystals

T T Basiev, I T Basieva, M E Doroshenko

When taking up some of Sergei Ivanovich Vavilov's scientific publications and his fundamental work — the book *Mikrostruktura Sveta* (*The Microstructure of Light*) [1] — one arrives at the conclusion that they laid the foundation for the modern nanophotonics of laser and luminescent materials.

Sergei Ivanovich stated that any light source may be characterized by three attributes: radiation energy, spectrum, and the state of polarization. In this regard, he emphasized that they are nothing more than average macroscopic characteristics. Concealed behind them is an extremely complicated microoptics world, due to which these average characteristics are formed. To investigate the nature of light and expose the relation between its properties and the properties of the elementary emitters generating light field, it is necessary to penetrate into this world of microoptics (or nanophotonics, as it is customarily called nowadays).

S I Vavilov assigned to microoptics (nanophotonics) the properties of very small emitters, the manifestations of the lifetimes of excited molecular states and, lastly, the interactions of luminous molecules with the surrounding medium. He placed special emphasis on the fact that the neighboring molecules determine the initial, principal, chain of optical excitation energy transfer (migration) in the medium [1].

Being aware that an increase in the particle concentration results in a shortening of the distance between optically active molecules and, accordingly, in a strengthening of the interaction between them, S I Vavilov and his collaborators studied this phenomenon in detail and discovered characteristic 'nontrivial' concentration dependences of the excited state lifetime, the polarization, and the yield of luminescence. As far back as the 1930s, S I Vavilov and his colleagues discovered that the concentration dependences of the excited state lifetime and the quantum yield were different; this was a direct indication that the kinetic curves of luminescence decay measured in their work were nonexponential.

Unfortunately, in those distant years there was technically no way of instantaneously exciting phosphor and measuring with high precision the kinetics of luminescence decay; nor was there a theory providing a quantitative description of the decay kinetics of a particle ensemble with the inclusion of microinteractions.

The first expressions for the decay kinetics of a statistical ensemble of luminous particles (donors) were due to Förster [2] (1948) and Galanin [3] (1955) in the form of a square-root dependence for the two-particle dipole–dipole quenching

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Uspekhi Fizicheskikh Nauk **181** (12) 1334 – 1340 (2011)
DOI: 10.3367/UFNr.0181.201112j.1334
Translated by E N Ragozin; edited by A Radzig

interaction and the donor–acceptor energy transfer:

$$I(t) \approx \exp\left(-\sqrt{Wt}\right), \tag{1}$$

where $I(t)$ is the normalized luminescence intensity, and W is the quenching rate.

More recently, this law was generalized for higher-order multipolar interactions. The general formula has the form [4–6]

$$I(t) \approx \exp\left[-(Wt)^{d/S}\right], \tag{2}$$

where S is the multipolarity order: $S = 6, 8$, and 10 for dipole–dipole, dipole–quadrupole, and quadrupole–quadrupole interactions, respectively, and d is the geometric dimensionality of space: $d = 1, 2, 3$.

It should be emphasized that so complicated form of luminescence decay kinetics is an important instrument for revealing the microstructure of light, which Vavilov spoke of, i.e., for determining the microefficiency (W_0) and multipolarity (S) of the dominant ion–ion interaction, the concentration dependence $W(c)$, the degree of particle ordering, and the dimension d of confined geometries in complex molecular systems of nanometer and atomic scales.

At present, the kinetics of energy transfer permits revealing not only the microoptics of interactions in a phosphor and a laser medium, but also the features of the spatial distribution of the NdO_8, PrO_8, and SmO_8 rare-earth ion molecular nanocomplexes in laser glasses.

An example is provided by the Nd–Nd concentration quenching in laser matrices. Not only may neodymium radiate energy, but two closely spaced ions may quench each other due to dipole–dipole interaction which transfers excitation to quenched levels. Furthermore, optical excitation may migrate from ion to ion and stay on the upper laser level.

The special feature consists in the fact that donor–donor interaction C_{DD} usually is strictly resonance, and its efficiency is therefore always higher than the efficiency of quenching donor–acceptor interaction C_{DA}. When $C_{DD} \gg C_{DA}$, the quenching kinetics for neodymium and many other ions is described by the simple expression

$$I(t) = \exp(-Wt), \tag{3}$$

with one parameter for the average quenching rate. On the face of it this is a facilitation for researchers, but in reality four characteristics enter into this parameter: the multipolarity of the interaction, the elementary transfer rate, the distance of closest approach, and the dimension of space. It was not clear how to determine these four unknown microparameters from one rate macroparameter, i.e., how to penetrate into microoptics from macrooptics. One way involves the use of low temperatures to 'freeze' migration [7, 8], while the other involves the utilization of samarium ions, whose migration interactions are strongly suppressed, $C_{DD} \to 0$ [9–11], to fulfill the function of probing (model) ions.

The general formula for the three-dimensional case of statical quenching ($C_{DD} = 0$) has the form (see, for instance, Refs [7, 9–11])

$$I(t) = \begin{cases} \exp[-W_{in}t], \quad W_{in} = \dfrac{7c_A C_{DA}}{R_{min}^S}, \quad t < t_b, & \text{(4a)} \\ \exp\left[-(W_F t)^{3/S}\right], \quad W_F = kc_A^{S/3} C_{DA}, \quad t > t_b, & \text{(4b)} \end{cases}$$

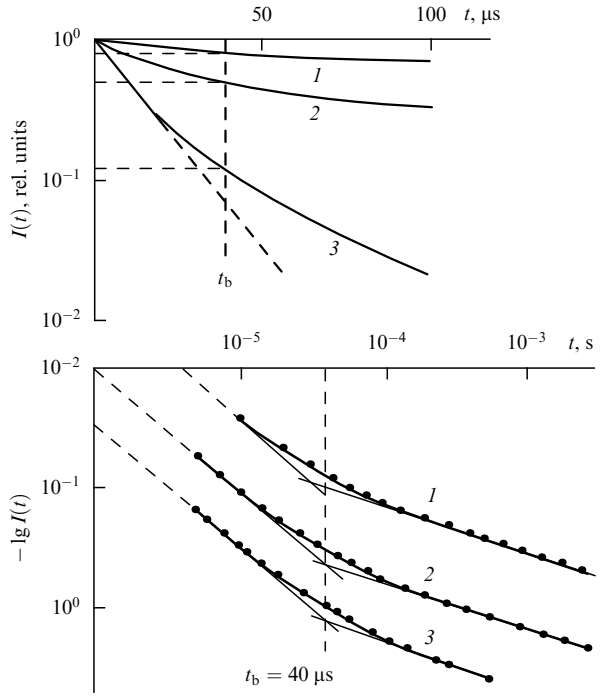

Figure 1. Sm–Sm quenching kinetics in lithium–lanthanum–phosphate glass for different Sm concentrations: Sm concentration of 2.5×10^{20} cm^{-3} (*1*), 9.2×10^{20} cm^{-3} (*2*), and 23×10^{20} cm^{-3} (*3*).

where W_{in} is the quenching rate at the initial stage, W_F is the quenching rate at the disordered stage described by the Förster law, t_b is boundary time of the change of these stages, R_{min} is the distance of the closest possible approach of active particles, k is a constant, and c_A is the acceptor concentration.

As discussed above, this more complicated, power-law form of kinetics is highly important for revealing the microstructure of intermolecular interactions, which Vavilov wrote of, i.e., for determining the multipolarity order, the microefficiency, and other transfer microparameters.

From the slope of the decay kinetics curve [7–11] rectified in a log-log plot of intensity vs time at a late stage of decay, $t \gg t_b$ (Fig. 1), we find the degree of nonexponentiality d/S (for Sm–Sm transfer, $d/S = 0.375$); hence, for the known dimension of space ($d = 3$), the multipolarity order $S(\text{Sm}-\text{Sm}) = 8$.

From the slope of the same kinetics curve, although plotted in the coordinates $t^{d/S} - \ln(I)$, we determine the average rate of nonexponential decay, $W_F \sim c_A^{S/3} C_{DA}$, whence we find the transfer microefficiency C_{DA} from the known S and the acceptor concentration c_A.

Interestingly, the initial decay stage, $t < t_b$, is indicative of ordered exponential kinetics, which reflects distance ordering in the location of luminescent particles or the volume around one particle, which is forbidden to approach. By substituting the already known microparameters S, C_{DA}, and the concentration c_A into the formula $W_{in} = 7c_A C_{DA}/R_{min}^S$ for the quenching rate at the initial stage, we find the last microcharacteristic, R_{min}, which characterizes the degree of short-range order in the ensemble. The energy transfer microparameters determined for several rare-earth ions in glass are collected in Table 1.

It is significant that R_{min} enters the expression for W_{in} (which also describes the quenching rate in a massive crystal in the presence of ultrafast migration) with a large exponent,

Table 1. Microparameters of Sm–Sm and Nd–Nd quenching in lithium–lanthanum–phosphate glass and of Eu–Eu migration in sodium–borosilicate glass [7–11].

Ions	S	C_{DA}	t_b, ms	$W(R_{min})$, s^{-1}	R_{min}, Å
Nd – Nd	6	0.03 $nm^6\,ms^{-1}$	0.59	1.7×10^3	5.1 – 5.4
Sm – Sm	8	0.23 $nm^8\,ms^{-1}$	0.04	2.5×10^4	5.6
Eu – Eu	10	4×10^{-3} $nm^{10}\,ms^{-1}$	0.12	8×10^3	4.7

which permits controlling the quenching rate and the quantum yield by selecting media with different R_{min}.

Cooperative nanodimensional energy transfer is another interesting example in which the kinetics are highly important.

Until 1999, developers of laser crystals believed that the Ce^{3+} ion, like La and Lu ions, is optically inactive (since it has no f–f transitions in the visible and near-infrared (IR) spectral ranges) and that it may be the main cation forming the laser matrix and not leading to the quenching of activators. However, it turned out that this is not so, and that the quenching by Ce ions does exist. We found that, for instance, for Nd^{3+} ions [12] (and more recently for the Ho^{3+} and Tm^{3+} ions as well [13]), the quenching rises sharply (quadratically) with increasing Ce^{3+} ion concentration. In particular, the lifetime of Tm^{3+} ions in CeF_3 crystals turned out to be 10 times shorter than in LaF_3. We undertook a comprehensive study of this new effect to find that it was due to the energy transfer from one donor ion, for instance, Tm^{3+}, simultaneously to two Ce^{3+} ions, which act as a common two-particle acceptor. In this case, the single-particle donor luminescence energy must be at resonance with the doubled Ce-ion absorption energy.

We also discovered the phenomenon of cooperative energy transfer in the case of Er → 3Ce quenching in lanthanum–cerium trifluoride [12] and in the Tb → 2Yb transfer in ytterbium garnet [14]; in the former case, three Ce ions acted as a single cooperative acceptor, and the concentration dependence of the quenching rate was cubic.

It should be emphasized that prior to our studies [12–16], experiments [17, 18] were carried out only on the cooperative transfer from a two-particle donor to a single-particle acceptor (2Yb → Tb up-conversion). The transfer probability was very low: the rate was equal to about 2 s^{-1}, which is well below the radiative transition rates for rare-earth ions, $10^2 - 10^5$ s^{-1}, and therefore it could not be measured directly.

We revealed that the radical difference of 'down-process' (i.e., of down-conversion — the cooperative energy transfer from a single-particle donor to two-particle acceptors) from up-conversion is the inclusion of summation over the set of pair acceptor versions throughout the cation (cerium) crystal sublattice, with the result that the total probability of transfer (of down-conversion) rises steeply (by several orders of magnitude).

In this case, the energy transfer rates are comparable to the radiative transition probabilities for donor ions, or even exceed them by an order of magnitude. These features should be taken into account in the development and investigation of laser materials, which has previously been overlooked. Cooperative sensibilization with down-conversion is of special interest, because it may permit advancing lasing to the mid-IR wavelength range (3–6 μm) and, furthermore, raising the quantum yield (200–300%) due to splitting one 'heavy' photon into several 'light' ones.

The problem of space-averaged cooperative energy transfer was theoretically considered assuming the continuous medium and a zero particle dimension [19–21]. In the case of quenching by two-particle acceptors, the kinetic dependence at long times has the following form

$$I_2(t) = \exp\left[-(W_2 t)^{d/(2S-d)}\right],$$
$$W_2 = \frac{d}{S-d}\left[\Gamma\left(\frac{2S-2d}{2S-d}\right)\right]^{(2S-d)/d}\frac{c_A^{2S/d}}{t_0}, \qquad (5a)$$

and in the case of quenching by three-particle acceptors, one finds

$$I_3(t) = \exp\left[-(W_3 t)^{d/(3S-2d)}\right],$$
$$W_3 = \left(\frac{d}{S-d}\right)^2\left[\Gamma\left(\frac{3S-3d}{3S-2d}\right)\right]^{(3S-2d)/d}\frac{c_A^{3S/d}}{2t_0}, \qquad (5b)$$

where W_2 and W_3 are the average cooperative quenching rates, Γ is the gamma function, and t_0 is the time of an elementary act of cooperative energy transfer to two or three acceptor particles located at the closest distance from the donor.

We performed Monte Carlo simulations and arrived at a good agreement between numerical experiment and the theoretical prediction by the example of a simple cubic lattice. Figure 2 shows cooperative energy transfer to two-particle acceptors. One can see that the slopes of simulated and theoretical intensity curves plotted on a logarithmic scale against time taken on the $d/(2S-d)$-power scale are in good agreement at a late stage, which testifies to the coincidence of the functional laws of decay in the theory and in the computer simulations. A characteristic feature of the thus found kinetic dependences is that the fractional exponent $d/(2S-d)$ of time t depends heavily on the interaction multipolarity S and the space dimension d. For instance, for a one-dimensional problem and a quadrupole–quadrupole interaction, the exponent of t is very small (0.053), while for a three-dimensional problem and a dipole–dipole transfer the exponent is much greater (0.333). So that the slope of the nonexponential kinetic dependence changes sharply with variations of multipolarity order S and space dimension d, and may serve as a 'probe' both for S and for d.

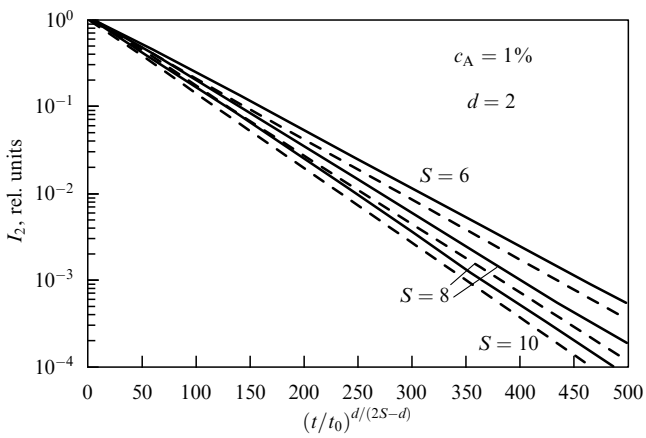

Figure 2. Cooperative luminescence quenching: simulations by the Monte Carlo method (solid lines), and analytical expression (5a) (dashed lines).

When we consider the dependence of the transfer rate on the number (concentration) of acceptors [see expression (5a)], we see that it also strongly depends on the dimension and multipolarity of interaction ($c_A^{2S/d}$). The exponent of the concentration dependence therewith is very large, from 4 to 20, unlike that for conventional concentration quenching.

In recent years, *nanostructured media* have occupied a special place in the physics of phosphors and laser media. Nanodispersed materials, photonic crystals, and nanopowders doped with fluorescent ions are important from the standpoint of using them in medicine, biology, and optics.

This brings up the question: how do the optical properties of luminescent media change in going over from massive bodies to nanodimensional ones? The objective was to determine the peculiarities and find analytical expressions for the relaxation kinetics of optically excited impurity ions in nanoparticles.

We applied the Monte Carlo method [22] to simulate the kinetics of energy transfer from donor ions to acceptor ions randomly located in spherical nanoparticles 5–50 nm in size, which is much smaller than the radiation wavelength. It was found that for nanoparticles the decay proceeded slower and the quantum yield was higher, and that this effect proved to be stronger for the nanoparticles of smaller size.

The analytical expression for the static quenching in nanoparticles was derived in the form [23, 24]

$$I_{\text{st\_nano}}(t) = \left(1 - \frac{(W_F t)^{1/S}}{2k_1 N_A^{1/3}}\right)^3 \exp\left[-(W_F t)^{3/S}\right] + \frac{3}{k_1}\frac{N_A^{1/3}}{(W_F t)^{2/S}} \exp\left[-\frac{(W_F t)^{3/S}}{2}\left\{1 - 2k_0 \frac{(W_F t)^{1/S}}{N_A^{1/3}}\right\}\right], \quad (6)$$

where k_0, k_1 are constants, and N_A is the average number of acceptors in one nanoparticle. For not-too-small nanoparticles, the second term in the curly brackets on the right-hand side of expression (6) may be discarded.

Expression (6), both with constant and with time-dependent amplitude coefficients of the summands, provides an adequate description of the simulated kinetics (Fig. 3). The initial stage of quenching kinetics in nanoparticles shows a power-law time dependence [the first term on the right-hand side of expression (6)], which is similar to the dependence for quenching kinetics in a bulk sample [see expression (4b)]. However, even when the luminescence intensity decays by only one-two orders of magnitude ($I(t) \sim 0.1-0.01$), the second term on the right-hand side of expression (6) comes into play, and a smooth transition to slower kinetics occurs. These kinetics are also linearized in $t^{3/S} - \ln(I)$ coordinates, but they have another macroscopic transfer rate. According to our analysis, the microphysics of quenching in nanoparticles manifests itself in the fact that those donors which are located in the volume of nanoparticles and have acceptors in the total sphere of quenching (in a 4π solid angle) initially decay. Then, as the bulk donors decay, the quenching of the donors that are located in the surface layer and have acceptors only in a quenching hemisphere (in a 2π solid angle) makes itself evident. To put this another way, a twofold lower number of acceptors come into play compared to the volume case, and the quenching proceeds with a $2^{S/d}$ lower macroscopic rate (4-to-1000 times lower).

The next example is *supermigration in nanoparticles*. As discussed above, in the energy transfer and luminescence quenching in the supermigration mode, when $C_{DD} \gg C_{DA}$

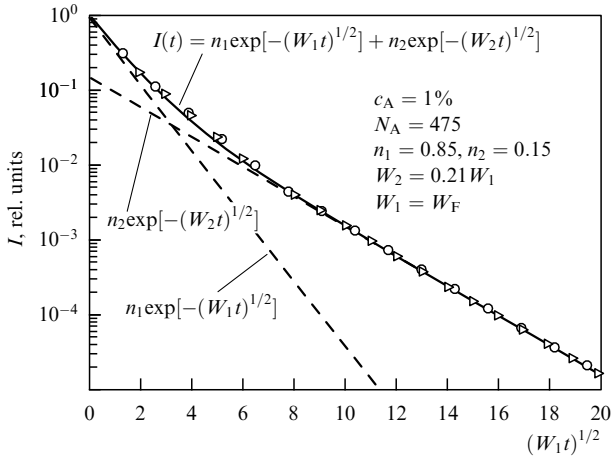

Figure 3. Two-stage kinetics of luminescence quenching in nanoparticles: Monte Carlo simulations (circles), and analytical expression (solid curve with triangles) consisting of two terms.

and the excitation migrates along donors quite fast, averaging of the quenching rates of different donors occurs, and then we normally observe the so-called kinetic limit — a monoexponential decay with a single average rate. And again this brings up the question: how is it possible to go over to microparameters, to microoptics, when we have only one rate macroparameter W (the average quantity) and many unknown microparameters?

It was found [25] that the kinetics in an ensemble of similar nanoparticles at long times cease to be monoexponential and pass into a nonexponential, power-law stage similar to statical quenching. And from this complex law it is possible to find, as before, all the sought-after microparameters: S, d, C_{DA}, and R_{min}. Roughly speaking, when we consider a bulk crystal with monoexponential decay kinetics, then on dispersing it to nanoparticles we arrive at nonexponential kinetics and next can determine all sought-after interaction microparameters in the system.

At long times, the exact analytical solution [25] has the form

$$I(t) = \exp\left[-N_D\left(\frac{W_F t}{N_D}\right)^{3/S}\left\{1 - \frac{9\Gamma(1-4/S)}{16\Gamma(1-3/S)} \times \frac{1}{R}\left(\frac{C_{DA} t}{N_D}\right)^{1/S}\right\}\right] \approx \exp\left[-N_D\left(\frac{W_F t}{N_D}\right)^{3/S} \times \left\{1 - \frac{0.6}{N_A^{1/3}}\left(\frac{W_F t}{N_D}\right)^{1/S}\right\}\right], \quad (7)$$

and this dependence agrees nicely with the data of computer simulations.

Our analysis gives evidence that solution (7) is similar to the static-case solution, with the exception of one important feature: the decay rate now depends on N_D — the number of donors in a nanoparticle, or the donor concentration. Previously, in a bulk specimen and in statics, this dependence was absent.

Figure 4 displays kinetic dependences for nanoparticles in this supermigrative mode, when $C_{DD} \gg C_{DA}$. For specimens of nanoparticles with different diameters D, as well as different donor and acceptor concentrations, one can readily observe the two-stage character of the kinetics, when the luminescence intensity is plotted on a doubly logarithmic

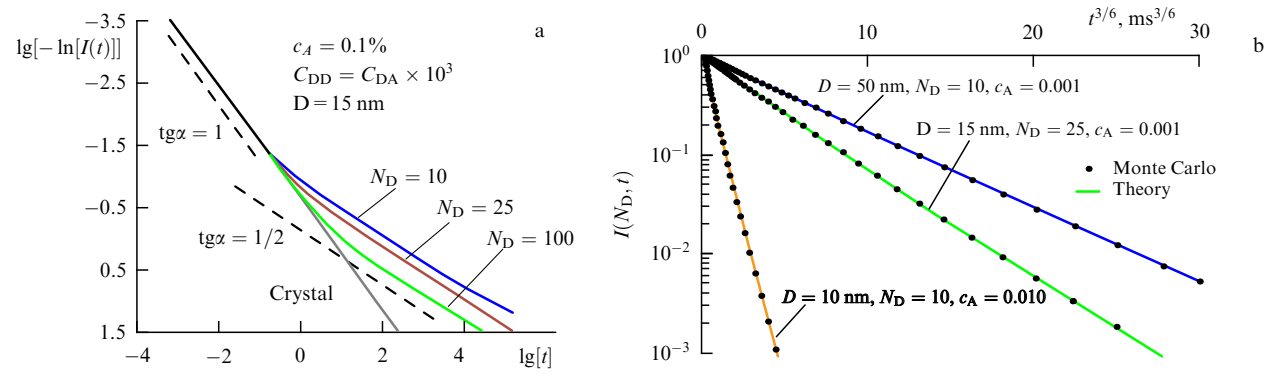

Figure 4. Two-stage kinetics of supermigrative luminescence quenching in a bulk crystal and nanoparticles with different donor concentrations; α is the slope, relative to the x-axis, of the kinetic curve plotted on a doubly logarithmic scale.

scale and time is plotted on a logarithmic scale: an exponential law for $t < t_b$ with a decay rate close to the kinetic limit in a bulk specimen is replaced with a power-law, nonexponential dependence for $t > t_b$ (Fig. 4a). A rectification of the kinetic curve in $t^{3/S} - \ln(I)$ coordinates is evident at long times (Fig. 4b). As before, from the slope of the curve plotted in $\ln(t) - \ln(\ln(I))$ coordinates for $t \gg t_b$, we find the exponent d/S of the power law and, hence, either the space dimension or the interaction multipolarity. Then, from the slope of the curve in $t^{3/S} - \ln(I)$ coordinates, we find the average quenching rate $W_{nF} = W_F N_D^{S/3-1}$; on substituting c_A, N_D, D, and S into it, we determine the microparameter C_{DA}. From the known t_b or from the decay rate at the initial stage, one can find the elementary donor–acceptor transfer rate at the distance of closest approach (in a donor–acceptor pair) or R_{min}.

Below, we enlarge on several achievements in the development of *modern laser materials* and on the interrelation between their properties and interaction microprocesses at a nanoscopic level in a laser medium.

Figure 5 illustrates a specimen of fluoride laser nanoceramics with no analogue in the world of laser materials, which was developed in our work. The fluoride base was selected, because alkali-earth fluorides possess a broad forbidden band and a narrow phonon spectrum, providing a unique possibility of making laser materials with a record broad wavelength spectrum, from the ultraviolet region to the mid-IR. Furthermore, these materials are sufficiently strong, are moisture-proof, tolerate a high level of doping, and possess a high thermal conductivity. Low refractive indices, both linear and nonlinear, permit obviating undesirable losses, spurious oscillations, stimulated Raman scattering, and self-focusing.

Rare-earth (RE) ions in fluoride crystals (for instance, Yb and Er ions) have a small lasing transition cross section and long metastable level lifetimes, which lower superluminescence losses and make the pump source cheaper. This is significant in the making of high-power laser amplifiers and oscillators.

Furthermore, a special feature of alkali-earth fluoride doping by RE ions consists in the fact that the RE ions enter them primarily in the form of clusters — two-, four-, and eight-ion clusters. This must manifest itself in luminescence and laser characteristics. Specifically, while the clusterization of neodymium ions is an adverse factor owing to the Nd–Nd cross-relaxation, which we considered above, for other ions, for instance, Yb, Er, Ho, and Tm, clusterization may well play a positive role. In particular, the theory of migration-

Figure 5. A girl holding in her hand a ceramics specimen obtained by the hot pressing technique.

controlled quenching suggests that the reciprocal of the quantum yield is proportional to the rate of optical excitation migration along laser-active ions and nanoclusters to quenchers. The migration rate, in turn, is proportional to the number of quenchers; uncontrollable impurity ions quite often act as quenchers, which usually imposes the requirement of high purity of initial materials and consequently leads to their high price. However, the quenching rate depends even more strongly on the laser ion concentration N_{las}, the clusterization degree n_{cl}, and the interaction multipolarity S [26]: $W_{mig} \sim c_A (N_{don})^{(S-2)/3} = c_A (N_{las}/n_{cl})^{(S-2)/3}$. Here, $N_{don} = N_{las}/n_{cl}$ is the concentration of clusters along which optical excitation migration takes place. Therefore, by raising the degree of clusterization ($n_{cl} = 2-8$), we can lower the migration rate $W_{mig} \sim (1/n_{cl})^{(S-2)/3}$ by a power-law factor [the exponent $(S-2)/3$ varies from 4/3 to 8/3] and thereby weaken the quenching of excitations by a factor of 6–100 (!), depending on the multipolarity order S. That is, by going over

to cluster activation, it is possible to moderate quenching and ensure a higher efficiency and a higher quantum yield in laser and luminescent materials, even for a higher number density of laser particles and quenchers, which makes it possible to relax the requirements on the purity of the starting raw material and to lower its price.

Ytterbium ions in different matrices have aroused considerable recent interest as the working ions under selective optical pumping by laser diodes due to their extremely simple diagram of electron energy levels and the consequential absence of different unfavorable processes, like cross-relaxation or absorption from the excited state, which significantly lower the efficiency of lasing , especially so for high dopant concentrations [27, 28]. The use of ytterbium ions with high enough concentration (2–9%) in fluoride crystals provides a way of obtaining broad absorption spectra, which are convenient to pump by diode lasers, and broad luminescence spectra, which make it possible to realize femtosecond lasing and output wavelength tuning over a rather broad range with a high efficiency [29].

Figure 6a demonstrates the best example of the lasing properties of Yb^{3+}-ion doped nanostructured crystals and ceramics under laser diode pumping. The differential efficiency amounts to 50% for crystals, and to 45% for ceramics [30]. A broad spectral lasing range, from 1.01 to 1.09 μm, permits making either tunable or femtosecond lasers with compact and inexpensive diode pumping [31, 32].

Another important example of laser fluoride ceramics is Nd-doped SrF_2 ceramics. For a low doping level (0.5%), this ceramics is characterized by a high thermal conductivity and a high quantum yield.

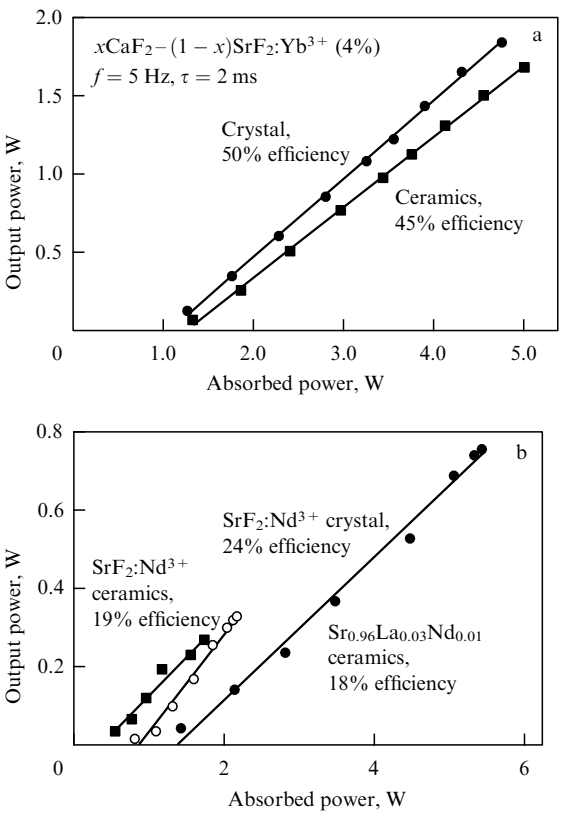

Figure 6. Comparison of lasing characteristics of (a) laser fluoride ceramics and a similar $CaF_2-SrF_2:Yb^{3+}$ single crystal, and of (b) $SrF_2:Nd^{3+}$ single crystal and $SrF_2:Nd^{3+}$ ceramics, and $SrF_2-LaF_3:Nd^{3+}$ ceramics under selective diode pumping and similar experimental conditions.

The highest-efficiency Nd-ion lasing is realized with Nd–F complexes (L-centers of tetragonal symmetry) possessing one of the shortest laser wavelengths in the $^4F_{3/2}-{}^4I_{11/2}$ optical transition (1.037 μm) and a lifetime of 1.1 ms of the metastable level, which is long for Nd ions [33]. The latter is of considerable importance in simplifying and making cheaper laser diode pumping, as well as in storing high inversion in the laser medium. Should the need arise to raise the concentration of active Nd ions, optically inactive La ions would be used as a co-activator to suppress the aggregation of Nd ions with each other and thereby suppress their self-quenching [34].

Figure 6b represents the best results in the generation of coherent radiation by neodymium ions in laser crystals and the nanoceramics of two types: SrF_2(Nd), and SrF_2(LaNd). A rather high differential efficiency was obtained in a quasi-continuous mode: 24% for the crystal, 19% for SrF_2(Nd) ceramics, and 18% for SrF_2(LaNd) ceramics in measurements under similar conditions [35]. The best result for the crystal in the absence of reflection loss was 37%, which gives hope that new ceramic materials will be competitive with a widely accepted neodymium laser glasses.

Another fresh example of newly developed laser ceramics is provided by $SrF_2:Pr^{3+}$ — the first ceramics operating in the visible spectral region (639 nm), where the requirements imposed on scattering loss are more stringent than in the near-IR region. Furthermore, the short-wavelength blue (445 nm) source required for the laser diode pumping of Pr ions complicates the attainment of lasing still more because of possible radiation scattering, induced loss, and photoionization. We managed to make an $SrF_2:Pr^{3+}$ ceramics which provides a low threshold of red (639 nm) lasing under continuous diode pumping and a sufficiently high efficiency (9%) [36–38]. This opens up the way for producing compact ceramic multicolor [red, green, blue (RGB)] coherent light sources for laser displays and projectors.

Let us consider the example of fluoride crystals, as well as CaF_2: Er and SrF_2: Er ceramics with Er_6F_{36} nanoclusters intended for mid-IR lasers. In this case, clusterization plays a positive role of fundamental importance: Er^{3+} ions possess a self-terminating laser transition $^4I_{11/2}-{}^4I_{13/2}$ (2.7 μm) with a long lifetime (9 ms) of the lower laser level, and lasing by single Er^{3+} ions is rapidly quenched owing to equalization of the populations of the upper and lower laser levels. Owing to short Er–Er separations in Er_6F_{36} nanoclusters, a strong up-conversion energy transfer $Er(^4I_{13/2}) + Er(^4I_{13/2}) \rightarrow Er(^4I_{11/2})$ with depopulation of the lower laser level $^4I_{13/2}$ and population of the upper energy level $^4I_{11/2}$ emerges under high-intensity pumping. This Er^{3+}-ion mode, which was first discovered in heavily doped YAG-Er^{3+} laser crystals [39, 40], subsequently enabled realizing the mode of cw lasing. For CaF_2: Er and SrF_2: Er crystals exposed to transverse laser diode pumping, it was possible to realize in this mode a three-micrometer cw lasing with a high efficiency (5–7%) and an output power of up to 2 W [41].

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PACS numbers: **01.65.+g**, **78.55.–m**, **85.60.–q**
DOI: 10.3367/UFNe.0181.201112k.1341

Advances in light sources and displays

A G Vitukhnovsky

Commemorating in 2011 the 120th anniversary of the birth of our outstanding compatriot Sergei Ivanovich Vavilov, an optical scientist, it is pertinent to note that his teacher Petr Petrovich Lazarev was the founder of the journal *Uspekhi Fizicheskikh Nauk*. This relationship imposes certain requirements on the report about modern light sources and alphanumeric displays, given below.

S I Vavilov laid the foundations of the science of luminescence in our country. Apart from Sergei Ivanovich's substantial contribution to the development of basic notions about the nature of luminescence, it was due to his organizational talent that our country obtained new light sources — the fluorescent lamps so well known to everyone. Under S I Vavilov's supervision, his associates and students set up an entire branch of power engineering and made a significant contribution to saving electric energy. The high-efficiency phosphors made with the direct participation of S I Vavilov enabled setting up domestic production of TV sets with the shortest possible delay.

A team of scientists supervised by S I Vavilov were awarded the 1951 Stalin (State) Prize for their achievements in the "Development of fluorescent lamps". All recipients of this major award need to be mentioned: S I Vavilov (awarded posthumously), V L Levshin, V A Fabrikant, M A Konstantinova-Shlezinger, F A Butaeva, and V I Dolgopolov. At present, the application of fluorescent lamps, primarily based on thoroughly modernized compact fluorescent lamps, is the solution of choice for illumination.

A few words about the history of light lamps. The year 1872 saw the advent of the first incandescent lamp, which completed the millennial search and revolutionized illumination technology. This happened in Russia, and the first to conjecture the air evacuation from a glass bulb and placing there a carbon rod incandesced by electric current was the brilliant Russian scientist Aleksandr Nikolaevich Lodygin. On May 20, 1873 lamps of his design went on in St. Petersburg. These were eight lanterns with Lodygin lamps. Unfortunately, the pioneer's laurels went not to A N Lodygin but to the outstanding American inventor Thomas Alva Edison, who received the corresponding patent [1]. Edison merely connected with wires a Lodygin

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Uspekhi Fizicheskikh Nauk **181** (12) 1341 – 1344 (2011)
DOI: 10.3367/UFNr.0181.201112k.1341
Translated by E N Ragozin; edited by A Radzig