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# Lasing of dyes in polymer matrices in the UV and visible regions

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**Abstract. Lasing properties and photostability of 4,4′-$CO_2C_4H_9$-bis-substituted para-terphenyl and azacoumarin (AC1F), emitting under excimer XeCl laser pumping in the blue-green spectral region, and of pyrromethene 580 and phenalemine 512, emitting under Cu laser pumping in the red spectral region, were studied in the PMMA matrix and ethanol solutions.**

## 1. Introduction

Tunable dye solution lasers are extensively used as sources of coherent radiation in laser isotope separation, remote probing of gases and liquids, initiation of chemical reactions, etc. [1]. However, laser media in the form of solutions are inconvenient to use in certain respects. It is evident that the feasibility of using solid-state active laser media (ALM) would make them more compact, remove inhomogeneities caused by fluid flow fluctuations, and eliminate solvent evaporation.

In this paper, our attention is focused on solid-state organic ALM on the basis of organic compounds introduced in polymethyl methacrylate (PMMA). However, note that tunable lasers may have active media of other kinds. Among them are ALM with colour centres, porous glasses activated with dyes, etc. Advantages of polymer ALM are as follows. They emit in a wide spectral range (from the blue to the red region), have high efficiency and photostability (the latter is comparable with the photostability of solutions of organic compounds, especially in the red region), are optically homogeneous, and have a high transparency in the UV region (the transmittance of modified PMMA at 308 nm is $\sim 80\%$, which differs it from porous glasses).

Laser elements made of a microporous glass have a high radiation resistance and a rather high lasing efficiency (up to 45%) [2 – 4]. The main disadvantage of such ALM are an optical inhomogeneity of a matrix, strong scattering of light, considerable birefringence, and a low photostability. Note, however, that a considerable among of recent attention is given to the development of a composite on the basis of PMMA and porous glasses [5]. This material is close in transparency to PMMA, but its radiation resistance is higher and samples made of it are easier to process. The presence of PMMA in a composite provides a high emission efficiency of an organic dye because of their affinity.

As for colour centre lasers [6 – 9], their potential is questionable for several reasons. First, they work, as a rule, in the red region (typically, lasing is obtained at $\lambda > 0.7$ μm) and are unstable in the visible region. Second, our experiments with colour centres pumped by a copper vapour laser [10] showed that it is difficult to obtain the concentration of F centres corresponding to a dye concentration of $\sim 10^{-2} - 10^{-3}$ mol litre$^{-1}$ because an attempt to obtain such concentrations leads to the formation of parasitic colour centres, and the optical quality of a medium becomes unsatisfactory. Third, these media are unable to work with excimer laser pumping because of their photodestruction, and, therefore, active media with colour centres fail the competition with dyes in the UV and visible regions.

The first attempt to design solid-state lasers working on dyes in polymer matrices was made in 1967 – 1968 [11, 12], when lasing of rhodamines in PMMA was demonstrated. However, the lasing efficiency of such media and their photostability were low. Progress achieved in the 1980s in the development of new matrices possessing a high radiation resistance initiated the development of solid-state lasers using a dye in a solid matrix as an ALM [13 – 16]. In recent years, the synthesis of new laser dyes and the development of new methods of their introduction into matrices led to considerable progress in developing solid-state dye lasers suitable for practical applications [17 – 20].

PMMA still holds the greatest promise for dyes, because the structure of this matrix is the closest to that of the laser dyes; PMMA has a high optical homogeneity and readily lends itself to machining. Methods for its modification were found, which provide a considerable improvement in its radiation resistance and the photostability of a dye in it. The composites using a combination of PMMA and inorganic sol-gel materials offer promise [5].

Considerable progress was achieved in developing ALM for the red spectral region. When excited by radiation at 532 nm (the second harmonic of a Nd:YAG laser), solid-state ALM on the basis of pyrromethenes demonstrate high-efficiency (exceeding 50%) lasing and possess a high photostability (their service life is $\sim 10^6$ pulses) [21, 22]. These parameters are close to the corresponding parameters for sol-

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utions of these dyes and show the feasibility of designing solid-state tunable dye lasers in this region [23 – 25].

However, the problem of the development of a solid-state ALM that is able to provide efficient and stable lasing upon pumping by a copper vapour laser with a high pulse repetition rate (15 – 20 kHz) remains unsolved. In Ref. [26], the service life of one of the best ALM pumped by radiation of a copper vapour laser with average power of $\sim 2$ W and pulse repetition rate of $\sim 12$ kHz was 8 minutes ($6 \times 10^6$ pulses).

Solid-state ALM, providing efficient lasing in the blue-green region, are virtually absent [27 – 29]. This is caused by the fact that it is common to pump such active media by UV gas lasers, which require a high transparency and radiation strength of a matrix and a high photostability of a dye itself. A number of molecules lasing in matrices in the blue-green region is small (coumarins and benzimidazoles) [27, 28], and they are pumped, as a rule, by low-power XeCl and $N_2$ lasers [28, 29]. The most short-wavelength lasing in a solid-state active medium on the basis of Exalite 377-E in a sol-gel matrix pumped by a nitrogen laser (337 nm) was obtained in the 360 – 378 nm region [29]. Its efficiency was 1%, and the service life was $10^4$ pulses.

Our aim was to study solid-state ALM producing efficient and stable lasing in the blue-green region upon pumping by a XeCl laser ($E_p = 10 - 100$ mJ, $\tau = 40$ ns, $\lambda_p = 308$ nm) and by a dye laser ($\lambda_p = 375$ nm, $E_p = 30$ mJ, $\tau = 35$ nm) and in the visible region under pumping by a copper vapour laser ($\lambda_p = 510.6$ and 578 nm, average power up to 2.5 W, pulse repetition rate of 12 kHz, $\tau = 35$ ns).

## 2. Experiment

We studied solid-state ALM on the basis of substituted para-terphenyl (LOS-1), azacoumarin (AC1F), phenalemine 512 (Ph-512), and pyrromethene 580 (PM-580) in PMMA. The structural formulas of the compounds are presented in Fig. 1. Spectral, luminescent, and lasing properties of the compounds were studied in ethanol solutions and matrices with the aim of finding the effect of an aggregate state and intermolecular interactions on them.

In the case where active media (LOS-1, AC1F, and Ph-512) were pumped by a XeCl laser, we used the transverse excitation scheme. A portion of XeCl laser radiation was directed onto an energy meter to monitor the pump energy. A laser cavity was formed by a totally reflecting mirror and a cell window (a face of a polymeric sample). Polymeric samples were fabricated in the form of rectangular parallelepipeds of cross section $1 \times 1$ cm.

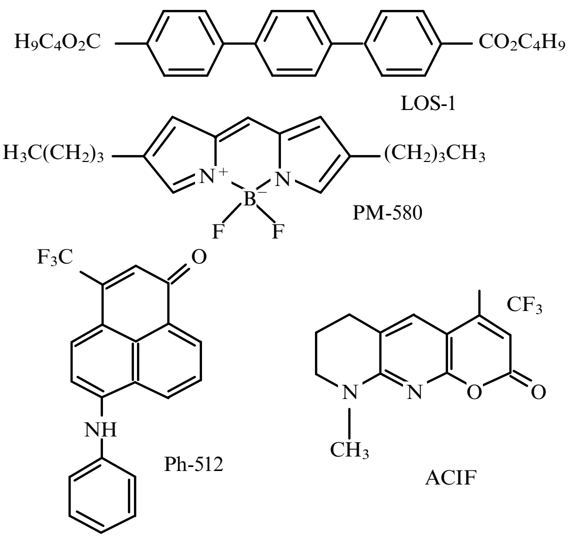

**Figure 1.** Structure of dye molecules.

The polymeric samples pumped by a Cu laser were disk shaped, and they were excited in the quasi-longitudinal and transverse schemes. In the first case, a copper bromide laser had the following beam parameters: 30 kHz pulse repetition rate, 30 μJ pulse energy, 40 ns FWHM, and 12 mm beam diameter. A sample was rotated in a cavity with a constant rate, the radius of rotation of an active region was $\sim 6.5$ mm, and the pump beam diameter on a sample was 0.4 mm, which gave the pump intensity $W_p = 0.8$ MW cm$^{-2}$. In the second case, a copper vapour laser had the 12 kHz pulse repetition rate, an average power up to 1.6 W, and the 35 ns FWHM. In the case of pumping by a Cu laser, we studied lasing characteristics of two solid-state samples activated with Ph-512 and PM-580 dyes.

The dye concentrations in PMMA were 0.1 and 1.0 mmol litre$^{-1}$ for LOS-1, 1.0 and 10 mmol litre$^{-1}$ for AC1F, 3.6 and 2.5 mmol litre$^{-1}$ for Ph-512, and 0.5 mmol litre$^{-1}$ for PM-580. The sample surfaces were not finished to laser quality because our goal at this given stage of work was to obtain a promising material. It is evident that the production of solid-state active elements on the basis of this material for tunable lasers will require a higher surface finish quality, which will increase the pump conversion efficiency.

When studying lasing properties of molecules, we recorded the lasing spectrum (by photoelectric means) and measured energy and time characteristics of radiation (with an IMO-2N power meter and an 'engineering vision' system connected to a personal computer). The absorption spectra were recorded on a Specord M40 spectrophotometer, and the fluorescence spectra were recorded on a Hitachi 850 spectrofluorimeter.

As a measure of photostability of active media, we used the pump energy per unit volume of an active medium decreasing the lasing efficiency by a factor of two $P_{0.5}$ and the quantum yield of photodisintegration $\gamma$, which was estimated by the formula $\gamma = N_{\rm ph}/N^*$, where $N^*$ is the number of excited molecules and $N_{\rm ph}$ is the number of phototransformed molecules per unit volume. The quantity $N_{\rm ph}$ was estimated from a change in intensity in the long-wavelength absorption band under small irradiation doses, when the effect of photoproduct absorption was insignificant.

We also studied the radiation resistance of the matrix at different pump radiation wavelengths. A PMMA sample having the same size as active elements was exposed to focused beams of an excimer laser ($\lambda = 308$ nm, $\tau = 40$ ns) and dye lasers ($\lambda = 373$ and 470 nm, $\tau = 30$ ns). In a wavelength region of 373 – 470 nm, the material is transparent, and its absorption coefficient at 308 nm is 0.3 cm$^{-1}$.

The studies were carried out by the method close to the one described in Ref. [30]. The radiation strength was characterised by the threshold number of pulses producing at the given radiation intensity the first scattering point in the bulk of a sample. The scattering was observed visually at the moment a pulse travelled through a sample. The error of repeated measurements of lasing efficiency was $\sim 5\%$. The error of determining the service life from the measurements of lasing efficiency and the pump energy per unit volume did not exceed 10 – 12%.

**Table 1.** Lasing characteristics of LOS-1 and AC1F in ethanol and PMMA.

| Compound | Solvent | $C$/mmol litre$^{-1}$ | $\lambda_{\text{fl}}$/nm | $\lambda_{\text{g}}$/nm | $\Delta\lambda_{\text{g}}$/nm | $\eta$ (%) | $P_{0.5}$/J cm$^{-3}$ |
|---|---|---|---|---|---|---|---|
| LOS-1 | PMMA | 0.1 | 365 | 365 | 9 | 17.6 | $20 \pm 2$ |
| | | 1 | 367 | 365 | 6.6 | 17.5 | $84 \pm 8.4$ |
| LOS-1 | Ethanol | 0.1 | 373 | 373 | 6.5 | 25 | $26 \pm 2.6$ |
| | | 0.5 | – | – | – | 40 | $150 \pm 15$ |
| | | 1 | – | – | – | 38 | $175^* \pm 17.5$ |
| AC1F | PMMA | 1 | 467 | 465 | 23 | 1.7 | $20 \pm 2$ |
| | | 10 | 477 | 475 | 18 | 12.5 | $87 \pm 8.7$ |
| AC1F | Ethanol | 1 | 480 | 498 | 15 | 14 | $48 \pm 4.8$ |
| | | 2.5 | – | – | – | 25 | $250 \pm 25$ |
| | | 10 | – | – | – | – | $500^* \pm 50$ |

*Corresponds to $\eta/\eta_0 = 0.8$, where $\eta_0$ is the maximum efficiency.

When estimating power density, we used the pump beam prints on photosensitive paper placed on the input face of a sample. Their size was measured under a microscope with an error of 0.05 mm. Note that the area measured in this way agrees within an error of 10% with the half-width of the radiation distribution profile measured by an optical multichannel analyser. Thus, the radiation power density was estimated with an error of 10 – 12%.

The quantum yield of phototransformation was estimated with an error of 10%, which was determined mainly by the error of absorbed-energy measurements. As for the radiation resistance of the matrix, it was determined by our method with an error of 1 – 2 pulses.

## 3. Discussion of the results

### 3.1 Blue-green spectral range. Lasing properties and photostability of dyes

Fig. 2 presents the absorption and fluorescence spectra of ethanol solutions of LOS-1 and AC1F. The spectra of dyes in PMMA are shifted to the short-wavelength region by approximately 10 nm. The excimer laser radiation corresponds to the maximum of the long-wavelength absorption band of LOS-1, and this provides minimum Stokes loss, which is of particular importance for polymeric materials because they are prone to local heating due to a low thermal conduction of the matrix.

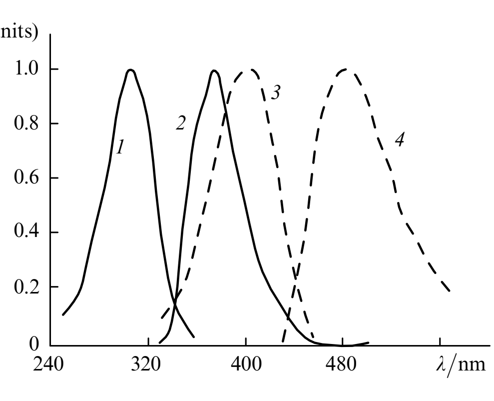

**Figure 2.** Absorption (**1, 3**) and fluorescence (**2, 4**) spectra of LOS-1 (**1, 2**) and AC1F (**3, 4**) in ethanol.

Table 1 presents the lasing characteristics of the compounds studied here and the quantity $P_{0.5}$ for the ALM on their basis, which characterises the resource for their operation. For the LOS-1 concentration $C = 0.1$ mmol litre$^{-1}$, the lasing efficiencies in ethanol and PMMA differ insignificantly (they are 25 and 17.5%, respectively). This concentration is characterised ($K_{308} \sim 5$ cm$^{-1}$). As a result, both surface and deep layers of a sample are involved in lasing. At $C = 1$ mmol litre$^{-1}$, the coefficient $K_{308}$ reaches 50 cm$^{-1}$ and because of this lasing, both in a solution and in PMMA, is developed near the surface of a sample. This fact suggests that one of the reasons behind the difference in lasing efficiencies for ethanol ($\eta = 38\%$) and PMMA (17.6%) at this concentration is an insufficient surface finish.

The maximum lasing efficiency for AC1F in PMMA pumped by an excimer laser was 12.5% (for an AC1F concentration of 10 mmol litre$^{-1}$). A low efficiency at $C = 1$ mmol litre$^{-1}$ is associated with a weak pump radiation absorption under these conditions. Indeed, in the case where the sample was pumped by radiation of a LOS-1 dye laser ($\lambda = 373$ nm), the efficiency increased up to 19% because the absorption coefficient at this wavelength exceeded the value at 308 nm by a factor of seven.

From Table 1, it follows that the resources for operation of LOS-1 in ethanol and PMMA at $C = 1$ mmol litre$^{-1}$ are close to one another. An increase in concentration up to 1 mmol litre$^{-1}$ leads to a proportional increase in the service life in ethanol, whereas the service life in PMMA increases by a factor of about four. It is obvious that this difference is associated with the fact that the pump radiation causes photolysis of PMMA, which has a noticeable absorption at $\lambda = 308$ nm. The matrix photodestruction products, which are formed in this process, are able, in turn, to cause addition decomposition of dye molecules and a decrease in the service life of the active medium. Similar concentration dependences of $P_{0.5}$ were observed for the AC1F dye. The dependences of the lasing efficiency of LOS-1 and AC1F in ethanol and PMMA on the pump intensity are presented in Figs 3 and 4. One can see that the optimum efficiencies are obtained at rather high intensities of $\sim 15 - 20$ MW cm$^{-2}$.

In addition to the lasing characteristics, we studied the photostability (the quantum yield of photodisintegration) of LOS-1 and AC1F in ethanol and PMMA. The photostability of dye molecules in a solution and a polymeric matrix was studied in close experimental conditions (the pump spot was

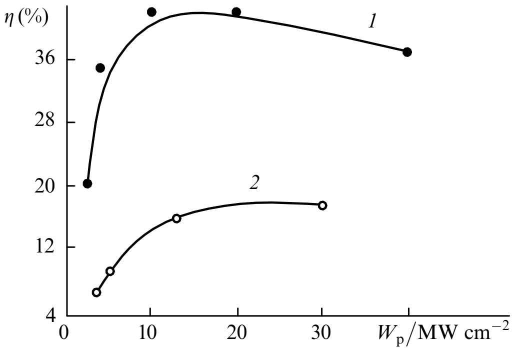

**Figure 3.** Dependences of the lasing efficiency of LOS-1 in ethanol ( 1 ) and PMMA ( 2 ) on the pump intensity.

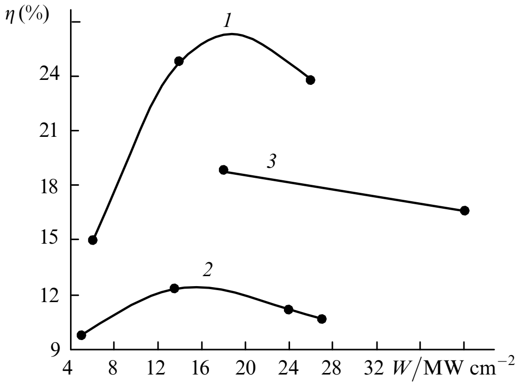

**Figure 4.** Dependences of the lasing efficiency of AC1F in ethanol ( 1 ) and PMMA ( 2, 3 ) on the pump intensity of radiation with $\lambda = 308$ ( 1, 2 ) and 375 nm ( 3 ).

$0.9 \times 1.3$ cm in size, liquid and polymeric samples were 1 and 0.8 mm thick, respectively, and the XeCl laser radiation intensity was 0.3 MW cm$^{-2}$ ). Table 2 presents the molecular photostability of ethanol solutions and polymeric samples. One can see that the stability of LOS-1 in ethanol is higher than the value for PMMA. The opposite relation is observed for AC1F.

Because the service life of an active medium is determined not only by the molecular photostability, but also by the absorption of photoproducts in the pump and lasing regions, we present the absorption coefficients of photoproducts in the lasing region ($K_g$) and in the pump region ($K_p$) for a fixed energy pumped into a medium in Table 2. The energy pumped into unit volume was 90 J cm$^{-3}$ for LOS-1 in ethanol solutions and PMMA and 60 J cm$^{-3}$ for the AC1F-containing samples. One can see that the photoproducts formed in PMMA had a higher absorption, both in the lasing and pump regions, than the photoproducts formed in ethanol solutions. It is likely that this is the dominant fact responsible for a lower service life of the compounds under study in PMMA.

The study of fluorescence of illuminated samples showed the presence of emission bands of photoproducts with maxima at $\lambda = 435$ and 480 in ethanol and $\lambda \sim 430$ and 455 nm in PMMA in addition to the fluorescence of the initial compound LOS-1. The fluorescence bands of photoproducts in ethanol and PMMA have close positions. It is likely that their molecular structures are close as well. As for the AC1F dye, we did not observe for it fluorescent photoproducts in ethanol solutions at the given exposure, whereas the PMMA samples showed the fluorescence of photoproducts near $\lambda = 370$ and 540 nm.

The dependences of the radiation resistance of PMMA on the wavelength and the radiation intensity are shown in Fig. 5. As expected, the radiation resistance of the matrix at the pump wavelength $\lambda_p = 308$ nm is considerably lower than the resistance at $\lambda_p = 373$ and 470 nm. The damage threshold for an intensity of 50 MW cm$^{-2}$ (2 J cm$^{-2}$) at $\lambda_p = 308$ nm is 1 – 2 pulses. For all the other experimental points on the curves, we observed the so-called accumulation effect. In this case, the damage was observed upon the introduction of a certain pump energy into a sample.

### 3.2 Red spectral region

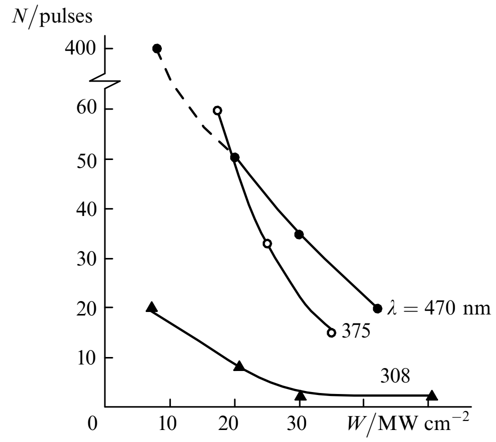

**Figure 5.** Dependences of the radiation resistance of the PMMA matrix without a dye on the pump radiation intensity at different wavelengths.

As noted above, a number of dyes, when pumped by the second harmonic of solid-state lasers ($\lambda_p = 532$ nm), produce efficient lasing in this region. A copper vapour laser ($\lambda_p = 510.6$ and 578 nm) is unsuitable for pumping solid-state active media because the operating life of such media at a high repetition rate is very short. However, laser systems on the basis of solid-state active media capable of efficient conversion of copper vapour laser radiation might offer considerable promise, provided the duration of the operating life was long.

**Table 2.** Molecular photostability of the compounds and the absorption coefficients of photoproducts in the pump and lasing regions.

| Compound | Solvent | $C$/mmol litre$^{-1}$ | $\gamma = N_{ph}/N^*$ | $K_g$/cm$^{-1}$ | $K_p$/cm$^{-1}$ |
|---|---|---|---|---|---|
| LOS-1 | Ethanol | 0.1 | $10^{-4}$ | ~0 | – |
| | PMMA | | $2 \times 10^{-4}$ | 0.62 | – |
| AC1F | Ethanol | 1 | $2 \times 10^{-3}$ | ~0 | 0.4 |
| | PMMA | | $10^{-3}$ | 0.4 | 1 |

In this work, PM-580 was excited in the quasi-longitudinal scheme by the Cu laser radiation. The conversion efficiency was 1.2%, and the number of pulses formed in an active region of volume 0.04 cm$^3$ at $\lambda_p = 572$ nm was $2.4 \times 10^6$. We found that this sample could be used to convert the copper laser radiation with $\lambda = 510.6$ nm into the radiation with $\lambda = 578.2$ cm. The gain $K_{am} = 1.8$ was calculated as the ratio of the average power measured at the output of the sample in the presence of the line with $\lambda = 510.6$ nm to the average power measured at the output of the sample in the line with $\lambda = 578.2$ nm. In the latter case, the line with $\lambda = 510.6$ nm was rejected by a filter.

Phenalemine 512 was pumped in the transverse scheme, which was chosen to decrease the pump intensity below the radiation damage threshold of the polymer [31]. A sample represented a disk 32 mm in diameter with a height of 8 mm. It was positioned in a plane-parallel cavity, fastened to it, and the whole assembly was mounted on a rotary table. The wobbling of the rotation axis of the table and the imperfection of the disk geometry and the faces caused partial misalignment of the cavity and a decrease in the dye conversion efficiency. Because of this, our study was aimed at measuring characteristics determining the resource for operation of a solid-state element. The results of our measurements are presented in Fig. 6. One can see that the maximum conversion efficiency of 4.5% was obtained for a sample with concentration of 2.5 mmol litre$^{-1}$.

The dependence of the efficiency on the sample irradiation time is of considerable interest. The efficiency is restored upon an interval during which a sample is not exposed to pump radiation (the interval length is specified in captions of Fig. 6). This form of the dependence may be associated with the fact that the formation of photoproducts in a sample under pump radiation goes on in two steps.

The first stage represents the formation of highly active radicals of dye molecules whose mobility and activity in a matrix are lower than in a solution. Upon the termination of pumping, when the conversion efficiency changes by 20–40%, radicals recombine during a pause, the concentration of active molecules is restored, and the final product is virtually absent. The second stage represents the attachment of photodisintegration products of polymeric molecules to radicals and the formation of stable oligomers. Their accumulation in a sample and a decrease in the initial concentration of active molecules lead to a decrease in the conversion efficiency of a sample.

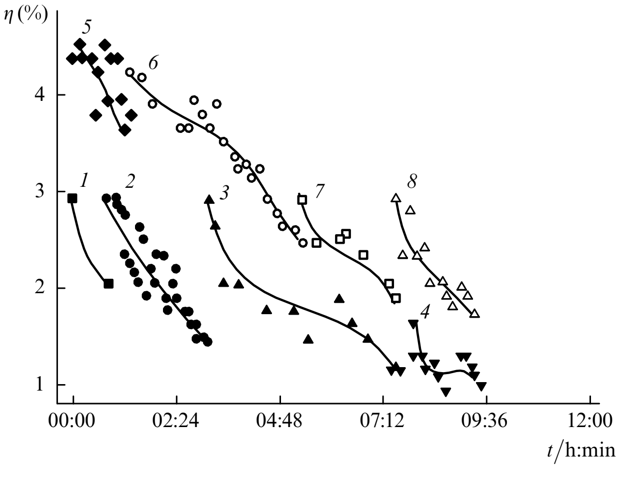

**Figure 6.** Plots characterising the resource for operation of Ph-512 in PMMA with $C = 3.6$ (1–4) and 2.5 mmol litre$^{-1}$ (5–8) for different energies pumped into a unit volume of a medium: 24 (1), 67.2 (2), 124.8 (3), 109.71 (4), 54.47 (5), 163.4 (6), 88.5 (7), and 69.93 kJ cm$^{-3}$ (8). Pauses between the measurements were 1 h (curves 6 and 7), 12–h (curves 1 and 2, 5 and 6), 48 h (curves 2 and 3, 7 and 8), and 264 h (curves 3 and 4).

The resource for the operation of solid-state elements containing Ph-512 with concentrations $C = 3.6$ and 2.5 mmol litre$^{-1}$ was 150 and 220 kJ cm$^{-3}$, respectively, which is equivalent to $6 \times 10^8$ pulses. The result considerably exceeds the value obtained in Ref. [26], where solid-state elements activated with F1 dye ($\lambda_p = 600$ nm) were pumped by a copper vapour laser with identical parameters. In this work, the service life reached $5 \times 10^6$ pulses, with efficiency equal to 3.5%.

It was of interest to study lasing characteristics of PM-580 and Ph-512 in a matrix and a solution pumped by XeCl laser radiation. Note that the lasing threshold of Ph-512 in a matrix under these conditions is rather low (below 2 MW cm$^{-2}$). The lasing characteristics of Ph-512 in PMMA and ethanol are presented in Table 3. The resource for operation of Ph-512 in PMMA pumped by high-intensity radiation of a XeCl laser (39 MW cm$^{-2}$) was about 200 J cm$^{-3}$. At a lower pump intensity of 5 MW cm$^{-2}$, the resource increased by a factor of more than two and was equal to 570 J cm$^{-3}$. In this case, the efficiency was restored, like in the case of pumping by a copper vapour laser. Upon a 65 h pause in irradiation, the efficiency was restored by 17%.

The results presented here show that Ph-512 is a promising compound for the development of ALM pumped both by a copper laser and by an excimer XeCl laser. The resource for operation of this compound is high. It is likely that this is caused, first of all, by the presence of a trifluoromethyl group in the composition of a molecule, which leads to a decrease in the yield of photoproducts absorbing laser radiation [32, 33].

The results obtained for PM-580 pumped by XeCl laser radiation offer less promise. In the ethanol solution with $C = 2$ mmol litre$^{-1}$ (the solubility threshold), we obtained lasing at 550 nm with efficiency of 4.6%. The solution had a low photostability. The quantum yield of phototransformation was $\sim 10^{-2}$, which exceeds the value for Rhodamine 6G under the same conditions by a factor of more than ten. It is likely that these effects are caused by nonoptimum excitation conditions (excitation to high-lying electronic states) and an insufficient concentration, which leads to the fact that a portion of pump energy is not absorbed by a solution.

The lasing characteristics of PM-580 in a sol-gel matrix pumped by XeCl laser radiation were unsatisfactory too. The lasing efficiency at a pump radiation intensity of 26 MW cm$^{-2}$ was 2.3%, and the medium had a low photostability of the order of 100 pulses.

**Table 3.** Lasing characteristics of Ph-512 pumped by a XeCl laser ($W_p = 39$ MW cm$^{-2}$).

| $C$/mmol litre$^{-1}$ | Solvent | $\lambda_g$/nm | $\eta$ (%) | $P_{0.5}$/J cm$^{-3}$ |
|---|---|---|---|---|
| 2.5 | PMMA | 593 | 10.3 | 176 |
| 3.6 | PMMA | 608.6 | 10.5 | 200 |
| 3.6 | Ethanol | 623 | 20 | 200* |

*Corresponds to a decrease of initial efficiency by 20%.

## 4. Conclusions

Thus, we studied lasing properties of some dyes in solutions and matrices emitting laser radiation in the blue-green and red regions when pumped by an excimer XeCl laser and a copper vapour laser. The results of our study made it possible to find solid-state active media holding the greatest promise for use in laser systems.

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