

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Lt; 42.55.Mv; 42.60.Lh
DOI: 10.1070/QE2002v032n09ABEH002299

Efficient 510 → 578-nm conversion of emission of copper vapour lasers

A.B. D'yachkov, V.P. Labozin

***Abstract*. The results of experiments on the 510 → 578-nm conversion of high-power radiation from a copper vapour laser (CVL) in a dye cell are presented. The use of the efficient laser dye Pyrromethane 597 (PM-597) made it possible to convert the 120-W CVL radiation (72 W at 510 nm + 48 W at 578 nm) into 102-W radiation at 578 nm, which is equivalent to a conversion efficiency of 85 %. Photostability of the dye in various solvents is studied. The photostability (more than 45 GJ mol^{-1}) of PM-597 in *n*-heptane is found to be higher than that of Rh 6G in ethanol.**

Keywords: *laser dyes, dye photostability, copper vapour laser, frequency conversion.*

Pulsed dye laser radiation in the spectral range 600 – 670 nm is of considerable interest for laser isotope separation [1] and medicine (in particular, in laser dynamic therapy) [2]. However, the lasing efficiency decreases considerably if copper vapour lasers (CVLs) are used for pumping dye lasers emitting in the red spectral region [3]. This is explained by the fact that the absorption band of dyes lasing efficiently in this spectral range lies in the range 570 – 620 nm (Stokes – Lommel law). In addition, a CVL emits green and yellow components at 510 and 578 nm, respectively, the ratio of the intensities of these components being 1.5 – 2 during the optimal operation of a gas-discharge tube. Therefore, a major part of the CVL emission cannot be converted efficiently. The only exception may be in the case of the DCM dye for which the spectral shift between the absorption and fluorescence bands is anomalously large and attains values between 100 and 150 nm, depending on the solvent [5]. However, the conversion efficiency of the pump energy (510 nm) in this dye does not exceed 20 % [6], and is considerably lower than the efficiencies (50 % – 60 %) attainable in Rhodamine 101, Cresyl Violet, and Sulforhodamine 640 pumped at 578 nm.

The intensity of the yellow component can be increased by heating the CVL tube. However, this is acieved due to a decrease in the green-component power rather than an increase in the radiation power at 578 nm. We are not aware of any experimental evidence of a successful redistribution of the intensities of the emission lines of a copper vapour laser resulting in an increase in the yellow component without a noticeable decrease in the output power. A simple method for increasing the relative intensity of the 578-nm line of a CVL was proposed in Ref. [4]. For this purpose, the CVL radiation is focused on a dye cell in which the population inversion is created by the green line of the CVL (pumping) and is removed by the yellow line of the CVL (amplification). The most efficient enhancement of the relative intensity of the yellow 578-nm component achieved in this way was demonstrated in Ref. [7]. The CVL emission with an average power of 6.2 W (for a ratio of the green to yellow component intensity equal to two) was converted to emission at 578 nm with an average power of 4.2 W, which corresponds to a 66 % conversion efficiency of the CVL emission. The 510 → 578-nm conversion efficiency was 50 % in the Rh 6G dye used.

We will show below that the laser dye Pyrromethene 597 (PM-597) is much more efficient for this purpose.

Fig. 1 shows the optical scheme of the setup. An output radiation beam of diameter 32 mm and divergence 0.5 mrad from a CVL consisting of an oscillator and two amplifiers was focused by a spherical lens (*1*) on a dye cell (*2*). The output beam was collimated by a lens (*3*) placed behind the cell. To estimate the conversion efficiency of the radiation emitted by the CVL, the yellow line was separated with the help of a dichroic mirror (*4*) (transmitting 90 % of radiation at 518 nm and reflecting 99.5 % of radiation at 578 nm). The output power was measured with power meters (*5*) [Powermax 500D (Molectron, USA)], while the temporal

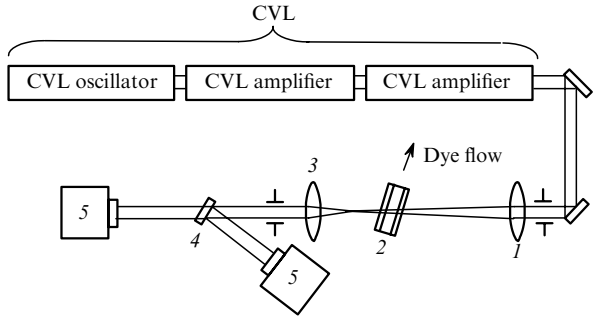

Figure 1. Optical scheme of the experiment on conversion of the emission spectrum of a CVL in a dye laser cell: (*1*) lens; (*2*) dye cell; (*3*) collimating lens; (*4*) dichroic mirror; (*5*) power meters.

A.B. D'yachkov, V.P. Labozin Institute of Molecular Physics, Russian Research Center 'Kurchatov Institute', pl. akad. Kurchatova 1, 123182 Moscow, Russia; tel.: (095) 196 76 60; fax: (095) 194 19 94; e-mail: adjach@imp.kiae.ru

Received 25 April 2002
Kvantovaya Elektronika **32** (9) 825 – 827 (2002)
Translated by Ram Wadhwa

characteristics of the radiation pulses were measured with a FK-26 photodetector.

The CVL pulse repetition rate was 10 kHz, and the FWHM of the pulses was 25 ns. The focal planes of a lens (*1*) at 510 and 578 nm differed slightly because of the lens chromatism. The dye cell was mounted along the beam in front of the focal plane. In this case, the pump radiation at 510 nm in the active region was confined within the reference beam at 578 nm, thereby eliminating spatial losses of the pump energy. The transverse size of the radiation at the input window of the cell was 1.5 – 2 mm (the peak pump power density in the dye was 10 – 15 MW cm^{-2}). The outer surfaces of the cell windows had antireflecting dielectric coatings, and the length of the active region (along the beam) was 3 mm.

The circulation system (with a working volume of 14 L) provided a flow rate of 28 L min^{-1} of the dye solution through the cell (the flow rate in the active region was 22 m s^{-1}). This corresponds to a complete replacement of the dye in the active region over a period equal to the interval between pulses. *n*-Heptane was used as the solvent, and the working concentration of the dye PM-597 was 2.6×10^{-4} mol L^{-1}.

The cell was irradiated by the CVL with an average power of 120 W (72 W at 510 nm + 48 W at 578 nm). The average radiation power at the cell output was 104.5 W (2.5 W in the green line and 102 W in the yellow line). Thus, the energy efficiency of the 510 → 578-nm conversion in the dye was 75 %. The total conversion efficiency (510 nm + 578 nm → 578 nm) was 85 %. The residual pump signal can be easily ascribed to a slight (2 – 3 ns) lead of the 510-nm pump pulse relative to the reference 578-nm pulse. Such an effect is typical for CVLs.

Apart from the efficiency, an important parameter determining a successful application of the dye is its photostability. The results of investigations of this parameter for different pyrromethene dyes are presented in Refs [8 – 11]. However, we are not aware of any data on the photostability of PM-597. According to Ref. [9], there is no single optimal solvent for pyrromethene dyes as far as the photostability is concerned.

The photostability of pyrromethene 597 (Exciton, USA) was determined in ethanol (C_2H_5OH) and *n*-heptane (C_7H_{16}), and that of Rhodamine 6G (Alfa-Aconix, Dolgoprudnyi, Russia), which is a standard laser dye, was determined in ethanol.

The optical scheme of the experiment is presented in Fig. 2. A closed dye cell (*3*) in a flat resonator was pumped by the second harmonic of Nd : YAG laser at 532 nm. One of the resonator mirrors (*1*) was dichroic and was used for a longitudinal coupling of the pump radiation (transmittance at 532 nm was 80 %, while reflection at wavelengths above 560 nm was more than 98 %). The output mirror (*2*) had a broadband dielectric coating with the transmission coefficient exceeding 75 %. The dye cell was 10-mm long. To reduce the Fresnel reflection losses, the external surfaces of the cell windows (K8 glass) were covered with an antireflection coating. The resonator had a length of 40 mm, the pump pulse repetition rate was 1 Hz, the FWHM of the pulse was 25 ns, and the pulse energy was 10 – 15 mJ.

The pump radiation was focused on the cell by a long-focus lens (*4*) so that the transverse size of the pump beam at the input window of the cell was 1 – 1.5 mm. The resonator axis and the pump beam formed a small angle

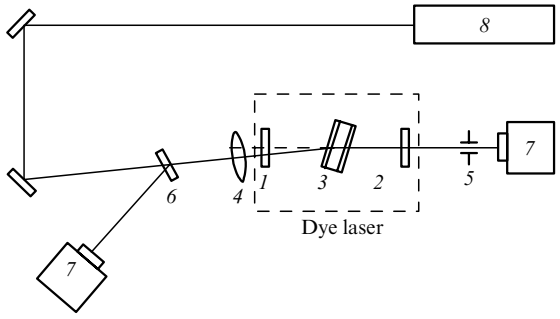

Figure 2. Optical scheme of the experiment on determining the photostability of the dye: (*1*) dichroic mirror; (*2*) output mirror; (*3*) dye cell; (*4*) long-focus lens ; (*5*) diaphragm; (*6*) beamsplitter; (*7*) photometer; (*8*) doubled Nd : YAG laser.

(3°) which ensured that the diaphragm (*5*) prevented the residual pump signal from entering a photometer (*7*). The energy of the laser and pump pulses was measured with nanosecond photometers (*7*).

In our experiments, the concentration *C* of the dye PM-597 in heptane and ethanol was 0.35×10^{-4} and 0.42×10^{-4} mol L^{-1} respectively, and the concentration of Rh 6G in ethanol was 0.21×10^{-4} mol L^{-1}. For such values of the concentration, the lasing efficiency was close to its maximum value.

Fig. 3 shows the dependence of the lasing efficiency on the pump energy absorbed by the dyes. The lasing efficiency was measured as the ratio of the laser pulse energy to the pump pulse energy. The absorbed pump energy was reduced to the molar number of dye molecules and had the dimensions GJ mol^{-1}. According to Ref. [12], the photostability of a dye was measured as the molar fraction of the absorbed pump energy for which the output laser signal intensity was halved.

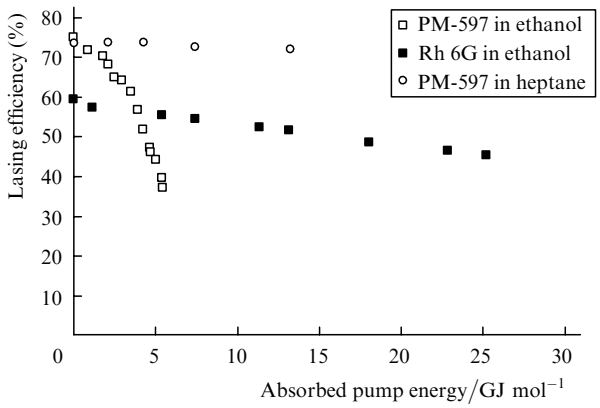

Figure 3. Dependence of the lasing effeciency on the pump energy absorbed in the dye.

We found that the photostability of PM-597 was the highest in *n*-heptane. For a pump energy of 45 GJ mol^{-1}, the lasing efficiency decreased from its maximum value no more than by 10 %. This is an order of magnitude higher than the photostability of PM-597 in ethanol (5 GJ mol^{-1}) and also higher than the photostability of Rh 6G.

The effect of concentration of the dye PM-597 on its photostability was studied in Ref. [10]. It was found that the photostability decreased with increasing concentration. To avoid a possible error in estimating the operating time of the amplifier cell without replacing (or addition) the dye, we performed an additional experiment. The solution of PM-597 in heptane was prepared at the concentration 2.1×10^{-4} mol L^{-1}, which is close to the working concentration of the dye in the amplifier cell. During the experiment, 0.25 cm^3 of the dye was exposed to radiation for seven hours (pulse repetition rate 10 Hz, pulse energy 9 mJ), which is equivalent to an absorbed specific energy of 45 GJ mol^{-1}. The lasing efficiency remained at the level of 75 %. However, the emergence of a weak pump signal at the output of the cell at the end of the experiment (bleaching effect) suggested a photodegradation of the dye.

Note in conclusion that an increase in the (510 nm + 578 nm → 578 nm) conversion efficiency of the CVL radiation to 85 % makes it possible to increase the efficiency of CVL-pumped dye lasers in the red spectral region. The photostability of the dye PM-597 in *n*-heptane, which is equal to 45 GJ mol^{-1}, means that an operating time of several hundred hours with no significant decrease in the conversion efficiency for a power of 120 W can be attained without any addition or replacement of the dye.

Acknowledgements. The authors thank the staff of the laser technology laboratory of the Institute of Molecular Physics, Kurchatov Institute Russian Scientific Centre for providing them an opportunity to use a high-power CVL.

References

1. Bass I.L., Bonanno R.E., Hackel R.P., Hammond P.R. *Appl. Opt*., **31**, 6993 (1992).
2. Loschenov V.B, Konov V.I., Prokhorov A.M. *Laser Phys*., **10**, 1188 (2000).
3. Morstyn G., Kaye A.H. *Phototherapy of cancer* (London: Harwood Academic Publishers, 1990) pp 55 – 65.
4. Kravchenko V.I., Litvinenko A.Ya, Smirnov A.A. *Sov. Tech. Phys. Lett*., **5**, 277 (1979).
5. Meyer M., Mialocq M J.C. *Opt. Commun*., **64**, 264 (1987).
6. Hargrove R.S., Kan T. *IEEE J. Quantum Electron*., **16**, 1108 (1980).
7. Coutts D.W., Ainsworth M.D., Piper J.A. *Opt. Commun*., **75**, 301 (1990).
8. Rahn M.P., King T.A., Gorman A.A., Hamblett I. *Appl. Opt*., **36**, 5862 (1997).
9. Pavlopoulos T.G. *Proc. SPIE Int. Soc. Opt. Eng*., **3613**, 112 (1999).
10. Mackey M.S., Sisk W.N. *Dyes and Pegments*, **51**, 79 (2001).
11. Pavloupolos T.G., Boyer J.H., Sathyamoorthi G. *Appl. Opt*., **37**, 7797 (1998).
12. Rahn M.P., King T.A. *Appl. Opt*., **34**, 8260 (1995).