第3卷 第1期
1983年1月

光学学报
ACTA OPTICA SINICA

Vol. 3, No. 1
January, 1983

Efficient pulsed Rh6G dye laser pumped by a copper vapor laser*

HUANG ZHENGUO
(*Institute of Electronics, Academia Sinica, Beijing*)

NAMBO KAZUMI AND SHIMIZU FUJIO
(*Department of Applied Physics, University of Tokyo, Japan*)

(Received 21 October 1981)

Abstract

A theoretical prediction on the performance of the pulsed dye laser pumped by a copper vapor laser was given. A high power efficient Rh6G dye laser pumped by a copper vapor laser was developed with longitudinally pumped geometry and jet stream on the basis of this theory. Average output power of 0.86 W for the Rh6G dye was obtained. Its efficiency was 31%.

Introduction

The copper vapor laser as a pump source of the dye laser instead of argon laser was attractive because its high efficiency of 1%. The total efficiency of dye laser pumped by a Cu laser can be 0.2%. This dye laser is a powerful tool for laser isotope separation, photochemistry and pico-second spectroscopy[1].

There are some troubles in using the Cu laser as pump source. It is very difficult to focus the Cu laser beam because of its larger diameter and larger angle divergence. Besides, the length of the dye laser cavity must be as short as possible to increase the round-trip number in order to have higher output power and better beam quality. To overcome these difficulties, an unstable cavity was used for the Cu laser to decrease the angle divergence[2]. On the other hand, the longitudinally pumped[3~5] or transversely pumped oscillator-amplifier geometries[6] were used to increase the output power and efficiency and to improve the beam quality.

In this paper we report the experimental result of the Rh6G dye laser with longitudinally pumped geometry and jet stream pumped by a copper vapor laser[7]. The result is compared with the analytic theory.

Theory

There were a lot of papers devoted to the discussion of dye laser theory[6,8].

In this paper we developed equations which are adequete to our purpose based on references [6, 8]. The characteristics of longitudinally pumped geometry were discussed.

* This paper was presented at the First Laser Conference of Japan in March 1981.

It was indicated that the longitudinally pumped geometry can produce high average output power and efficiency.

Fig. 1 is the level structure and kinetic processes of the dye used in the rate equation model. The relevant rate equations for the laser medium are:

$$\frac{dn_1}{dt}=\sigma_{01}(\lambda_p)\cdot n_0\cdot I_p-n_1/\tau_s-\sigma_e(\lambda_l)\cdot n_1\cdot I_l, \quad (1)$$

$$\frac{1}{c}\frac{\partial I_p}{\partial t}+\frac{\partial I_p}{\partial x}=-\left[\sigma_{01}(\lambda_p)\cdot n_0+\sigma_{12}(\lambda_p)\cdot n_1\right]\cdot I_p, \quad (2)$$

$$\frac{1}{c}\frac{\partial I_l}{\partial t}+\frac{\partial I_l}{\partial x}=\sigma_e(\lambda_l)\cdot n_1\cdot I_l, \quad (3)$$

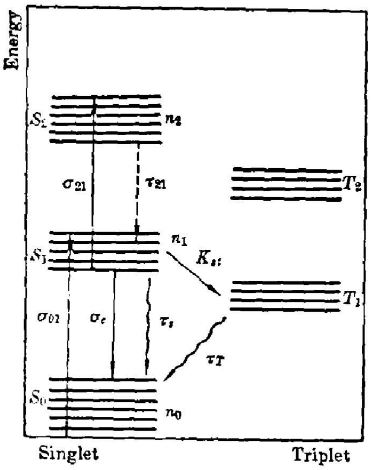


Fig. 1 Dye level structure and kinetic processes used in the rate equation model

where n_0 and n_1 are the ground and first excited singlet state dye population densities, σ_{01}, σ_{12}, and σ_e are ground state absorption, excited state absorption and stimulated emission optical cross section. τ_s is the spontaneous decay lifetimes, I_p and I_l are the pump laser and the dye laser intensities expressed in photons/sec·cm^2.

Several effects have been omitted[6] in eqs. (1)~(3), because they are not important for the copper vapor laser pumped dye laser. First, the triplet absorption effects have been omitted because the pumping laser duration (20 ns) is considerably shorter than the singlet to triplet intersystem crossing time constant K_{st}^{-1}(10^{-7} sec.). Second, the population n_2 was taken to be zero because the radiationless decay time ($\tau_{12}\sim10^{-12}$ sec.) is much smaller than τ_s(10^{-9} sec.). Finally, since the stimulated emission cross section $\sigma_e(\lambda_p)$ at the pumping laser wavelength and the absorption cross section $\sigma_{01}(\lambda_l)$ at the laser wavelength are small, both have been taken as zero. The steady-state solution is utilized because the dye spontaneous lifetime is much shorter than the pumping laser pulse width, and this is a very good approximation for the dye laser pumped by Cu laser.

The saturation gain of the dye laser, from (1) and (3), can be expressed as follows for a homogeneous laser transition:

$$\frac{1}{I_l}\frac{dI_l}{dx}=\frac{\alpha_0}{1+I_l/I_s}。 \quad (4)$$

where the small signal gain α_0 and the effective saturation flux I_s are

$$\alpha_0=\frac{n\sigma_e\tau_s\sigma_{01}(\lambda_p)I_p}{1+\sigma_{01}(\lambda_p)\tau_sI_p}, \quad (5)$$

$$I_s=\frac{1+\sigma_{01}(\lambda_p)\tau_sI_p}{\sigma_e\cdot\tau_s}, \quad (6)$$

and n is the dye number density (n_0+n_1). Except for the omission of $\sigma_{01}(\lambda_l)$, these expressions are the same as in reference[6]. In addition, from eq. (2) the pump intensity is obtained:

$$I_p(x)=I_p(0)\cdot\exp[-\sigma_{12}(\lambda_p)n+(\sigma_{12}(\lambda_p)-\sigma_{01}(\lambda_p))n_0]\cdot x. \tag{7}$$

In general, the first term of eq. (7) is greater than the second term. In order to obtain a closed form solution, it is assumed that the pump intensity has the approximate form:

$$I_p(x)=I_p(0)\cdot\exp[-\sigma_{12}(\lambda_p)\cdot nx]. \tag{8}$$

This assumption is exact if $\sigma_{12}(\lambda_p)=\sigma_{01}(\lambda_p)$ or $n\gg n_0$.

In order to obtain the expression of output power from the dye laser, we must integrate eq. (4) along the thickness of the dye jet, and assume that the dye laser beam and the pumping laser beam are collinear, though there is a small angle between them in practice.

The integration of eq. (4) along the dye oscillator axis x is just single pass saturation gain. It should be equal to the single pass loss in the steady state:

$$\int_0^d \frac{\alpha_0}{1+I_l/I_s}\,dx=f, \tag{9}$$

where f is the total losses including the scattering loss by the mirror, the jet and loss of output coupling of the mirror.

With above approximation, the integral of the left hand of the eq. (9) is straight forward as follows:

$$\frac{\sigma_e}{\sigma_{12}}\ln\frac{1+\sigma_e\tau_sI_l+\sigma_{01}(\lambda_p)\tau_sI_p(0)}{1+\sigma_e\tau_sI_l+\sigma_{01}(\lambda_p)\tau_sI_p(0)\cdot\exp(-\sigma_{12}nd)}. \tag{10}$$

After some simple manipulation, we obtained the dye laser intensity:

$$I_l=\frac{1}{\sigma_e\tau_s}\left\{\frac{\tau_s\sigma_{01}(\lambda_p)I_p(0)\cdot\left[1-\exp\left(\frac{\sigma_{12}}{\sigma_e}f-\sigma_{12}nd\right)\right]}{\exp\left(\frac{\sigma_{12}}{\sigma_e}f\right)-1}-1\right\}. \tag{11}$$

This expression of dye laser intensity is essentially the same as the expression (44) of reference[8]. The output power of the dye laser is:

$$I_0=TAI_l, \tag{12}$$

where T is transmission of the output mirror, A is the cross section of the beam waist of dye laser on the jet stream.

For the Rh6G dye and our particular dye laser apparatus, the parameters in (11) and (12) are as follows:

$\sigma_e(\lambda_l=575\,\text{nm})=1.5\times10^{-16}\,\text{cm}^2$, $\sigma_{01}(\lambda_p=510.6\,\text{nm})=\sigma_{12}(\lambda_p)=1.3\times10^{-16}\,\text{cm}^2$, $\tau_s=5\times10^{-9}$ sec., $n=(6\sim18)\times10^{17}/\text{cm}^3$, [for $(1\sim3)\times10^{-3}$ M/L concentration]. $d=10^{-2}$ cm (the jet thickness), $T=0.5$, $A=3.14\times10^{-4}\,\text{cm}^2$.

With these parameters, the equation (12) becomes:

$$\bar{I}_0=2.86\times10^{-3}[C\bar{I}_p(0)-1], \tag{13}$$

Where the $\bar{I}_0$ and $\bar{I}_p(0)$ are the average output power of the dye laser (575 nm) and the copper vapor laser (510.6 nm) expressed in Watt, respectively. The constant C depends on the loss f, the dye jet thickness d and the dye concentration n.

In Fig. 2 $\bar{I}_0$ is shown as function of $\bar{I}_p(0)$ for different values of loss f. The output power increases linearly with pump power. For the small loss, the efficiency is greater than 50%. The output power will be seriously decreased with increase of the loss. This fact shows that the decrease of the loss is important even in high gain laser.

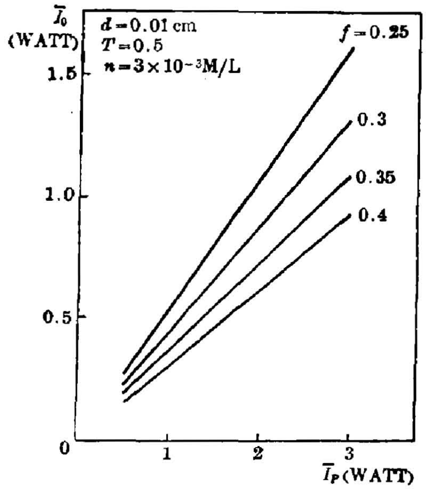


Fig. 2 Theoretical dependence of Rh6G dye laser average output power $\bar{I}_0$ on the Cu laser pump power $\bar{I}_P$

In Fig. 3 the dye laser output power is shown as a function of thickness d of the jet. The dye power does not increase when the thickness d is greater than 1 mm. It shows that the increase of the thickness does not increase the output power in longitudinally pumped geometry.

In Fig. 4 $\bar{I}_0$ is shown as a function of the dye concentration n. $\bar{I}_0$ slowly increases with increase of the concentration for $d=0.01$ cm, but when $d\geqslant0.1$ cm, $\bar{I}_0$ is independent of the concentration.

The theory shows that the longitudinally pumped geometry which has small dye thickness and large focused pump intensity can also produce high output power as in transversely pumped geometry which has small pump intensity and large dye gain thickness[6].

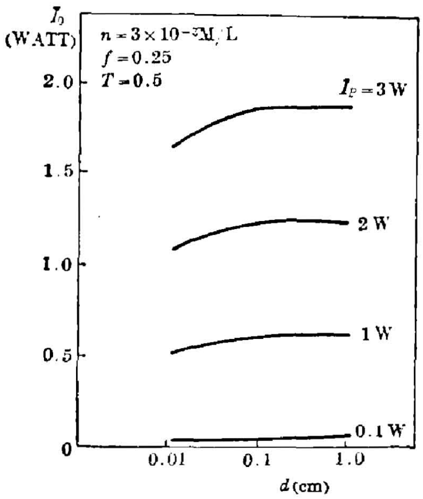
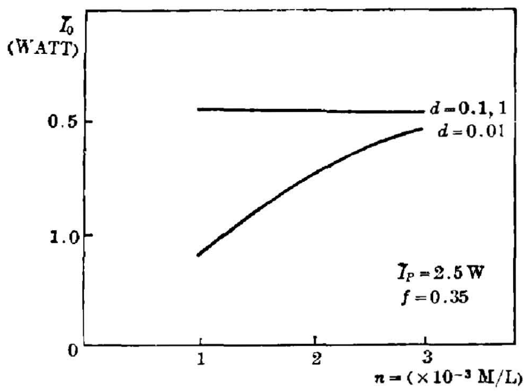


Fig. 3 Theoretical dependence of Rh6G dye laser average output power $\bar{I}_0$ on the thickness d of the dye jet



Eig. 4 Theoretical dependence of Rh6G dye laser average output power $\bar{I}_0$ on the dye concentration n

Experimental apparatus

The experimental apparatus used to investigate the longitudinal pump dye laser is shown in Fig. 5. The copper vapor laser 1 is used for pump source. In order to decrease the angle divergence, a planar dielectric mirror and a glass plate are used for the resonator. The windows are perpendicular to the discharge tube axis. They are accurately aligned to act as a Fabry-Perot etalon. With this arrangement, the angle divergence of the Cu laser is 1~2 mrad. The beam diameter is about 25 mm. The pulse repetition rate is 5 kHz. The average power used is about 5W in maximum (all line). The dye laser is excited only with $\lambda = 510.6$ nm green line deflected by two prisms 2. The pump radiation is focused by a Canon camera lens 3 ($F = 55$ mm, 1:1.2) into a planar jet of Rh6G dye dissolved in ethylene glycol 4. The jet stream has 0.1×4.3 mm dimension. The flow velocity of dye in the jet can be varied within the range 0~13 m/sec.

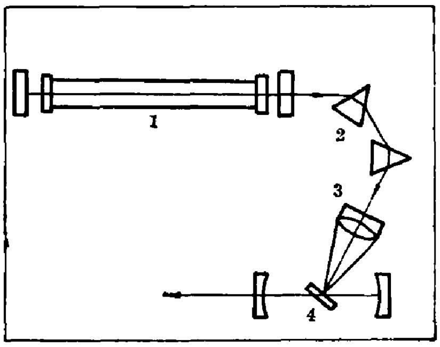


Fig. 5 Schematic diagram of apparatus

The focused pump spot on the jet is about 0.2 mm. A short length resonator is used in the dye laser. It consists of a spherical mirror with radius of curvature 30 cm and reflectivity 99.8% and an output mirror with radius of curvature 38 cm or infinity and reflectivity 50%. The length of resonator is about 3~4 cm. It can be varied to match the beam spot size on the jet stream. The concentration of Rh6G is $(1\sim3)\times10^{-3}$ M/L.

Experimental results

We determined the dependence of the average output power $\bar{I}_0$ and the efficiency of the dye laser on the average pump power $\bar{I}_p$ of the Cu laser (Fig. 6, 7).

The average output power of the dye laser increased linearly to 0.86 W when the pump power (510.6 nm) increased to 2.8 W. There is no any saturation tendency. This is consistent with the theory. The slope of the curve is smaller than the corresponding theoretical value. This is perhaps because of the large loss of the jet due to the scattering and the un-collinear of the pumping beam and the dye laser beam.

The efficiency of the dye laser first increases with the increase of pump power. But when the pump power is greater than 2 W, the efficiency becomes constant. The maximum efficiency in our experiment is 31%.

The dependence of the output power $\bar{I}_0$ on the concentration of Rh6G dye is shown in Fig. 8. The experimental curve resembles the theoretical curve. $\bar{I}_0$ increases with increase of the concentration at first, then there is a saturation tendency when the

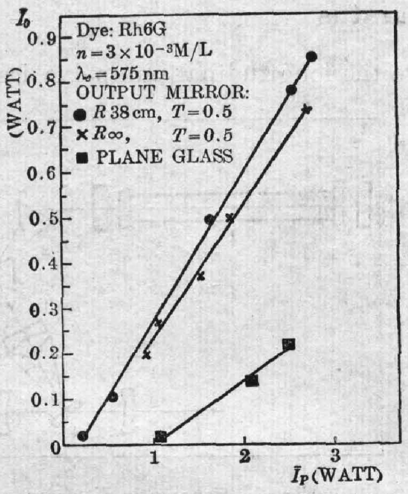


Fig. 6 Experimental dependence of Rh6G dye laser average output power $\bar{I}_0$ on the Cu laser pump power $\bar{I}_P$

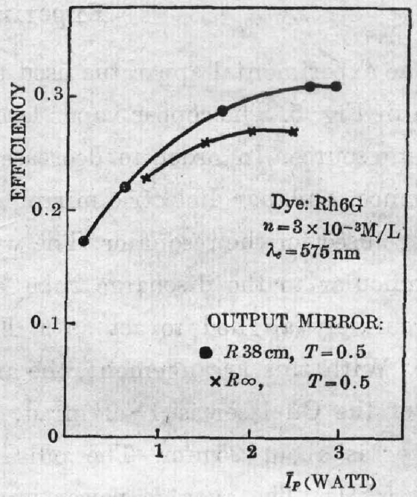


Fig. 7 Experimental dependence of Rh6G dye laser efficiency on the Cu laser pump power $\bar{I}_P$

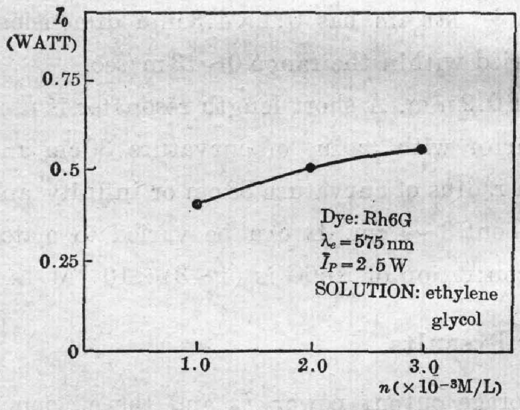


Fig. 8 Experimental dependence of Rh6G dye laser average output power $\bar{I}_0$ on the dye concentration n

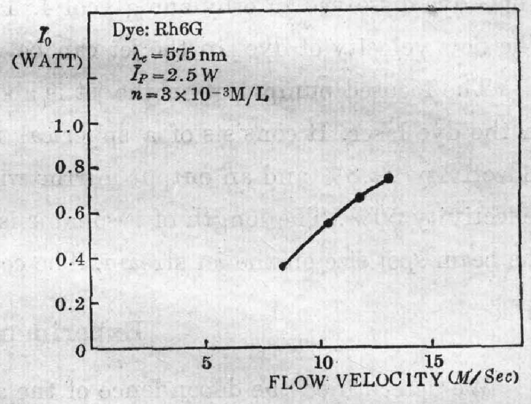


Fig. 9 Experimental dependence of Rh6G dye laser average output power $\bar{I}_0$ on the flow velocity of the dye solution

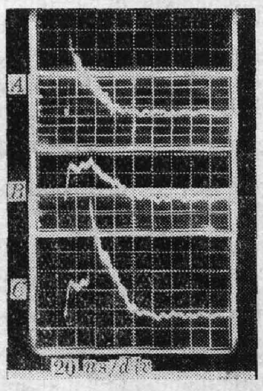


Fig. 10 (A) dye laser waveform (575 nm);
(B) copper vapor laser waveform (510.6 nm and 578.2 nm);
(C) the composition waveform of the dye laser and the copper vapor laser

concentration is greater than 3×10^{-3} M/L.

The dependence of the output power $\bar{I}_0$ on the flow velocity of the dye solution is shown in Fig. 9. Fig. 10 is the dye laser waveform.

Conclusion

Our experimental results and theory show that the dye laser pumped by copper vapor laser with longitudinally pumped geometry can produce high average power and high efficiency. The linear relation between the dye laser output power and pump power shows that high output power of dye laser can be obtained with increase of the pump power.

References

[1] GBL; *Phys. Today*, 1979, **7**, No. 1 (Jan), 17.
[2] R. S. Hargrove, R. Grove *et al.*; *IEEE J. Q. E.*, 1979, **QE-15**, No. 11 (Nov), 1228.
[3] C. D. Decker, T. S. Fahlen *et al.*; *J. A. P.*, 1975, **46**, No. 5 (May), 2308.
[4] L. V. Masarnovskii, A. N. Soldatov *et al.*; *Sov. J. Q. E.*, 1979, **9**, No. 7 (Jul), 900.
[5] K. I. Zemskov, A. A. Isaev *et al.*; *Sov. J. Q. E.*, 1976, **6**, No. 6 (Jun), 727.
[6] R. S. Hargrove, T. Kan; *IEEE J. Q. E.*, 1980, **QE-16**, No. 10 (Oct), 1108.
[7] Z. G. Huang, S. Kobayashi *et al.*; レーザー研究, 1981, **9**, No. 2 (Mar), 175.
[8] O. Teschke, A. Dienes *et al.*; *IEEE J. Q. E.*, 1976, **QE-12**, No. 7 (Jul), 383.

铜蒸气激光泵浦的高效脉冲若丹明 6G 染料激光器*

黄　振　国

（中国科学院电子所）

難波和身　清水富士夫

（日本东京大学工学部物理工学科）

提　　要

本文给出了铜蒸气激光泵浦的脉冲染料激光器性能的理论预测。根据这个理论，设计了一台用铜蒸气激光泵浦的、具有纵向泵浦结构和喷流的高功率高效率若丹明 6G 染料激光器。对若丹明 6G 染料，得到了 0.86 W 的平均输出功率，效率为 31%。

收稿日期：1981 年 10 月 21 日

* 本文曾在 1981 年 3 月的日本第一届激光学会上宣读过