

LASERS

PACS numbers: 42.55.Lt; 42.55.Xi; 42.60.Lh
DOI: 10.1070/QE2012v042n02ABEH014734

Diode-pumped caesium vapour laser with closed-cycle laser-active medium circulation

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Abstract. **The creation of a caesium vapour laser with closed-cycle circulation of the laser-active medium is first reported. The power of the laser radiation amounted to ~1 kW with the 'light-to-light' conversion efficiency of ~48%. Quasi-two-dimensional computational model of the laser operation that provides adequate description of experimental results is considered. Calculated and experimental dependences of the laser radiation power on the temperature of the cuvette walls, laser medium pressure and pump power are presented.**

Keywords: *caesium vapour laser, diode pumping, active medium circulation.*

1. Introduction

At present, significant progress in increasing the power of alkali metal vapour lasers pumped by laser diodes is observed [1–4]. The use of diode pumping allows conversion of low-voltage electric energy into the energy of narrow-band pump radiation with high efficiency $\eta_{\rm ld} \sim 40\% - 70\%$. High quantum efficiency of atomic transitions in alkali metals $\eta_{\rm q} = \lambda_{\rm p}/\lambda_{\rm las} =$ 95% for caesium and 98% for rubidium in combination with the possibility to control the linewidth and the gain of the metal vapour by varying the pressure and the temperature of the medium allows, according to our calculations, the conversion of the pump radiation into the laser one with the efficiency $\eta_{\rm pl} \sim 50\% - 60\%$. Thus, the total laser efficiency $\eta_{\rm las}$ may be as large as $\sim 20\% - 40\%$.

The population inversion and lasing on the D_1 ($^2P_{1/2} - {}^2S_{1/2}$) transition in the case of optical pumping of the D_2 ($^2S_{1/2} - {}^2P_{3/2}$) transition and populating the $^2P_{1/2}$ level in collisions of alkali metal atoms, occupying the $^2P_{3/2}$ level, with the atoms of buffer gas (Fig. 1) were first obtained in [5–7]. Later [8] it was shown that efficient population of the $^2P_{1/2}$ level occurs when ethane is used as a buffer gas. The efficiency of laser operation in early experiments was rather low, and the output power did not exceed a few microwatts. In 2003 a new concept was proposed, namely, a cw alkali metal vapour laser pumped by the radiation of laser diodes, with collisional broadening of D_2-line by helium in addition to the collisional mixing of upper energy states by light hydrocarbon molecules [9]. The concept implied pumping by commercial relatively cheap laser diodes with the radiation linewidth up to a few nanometres and allowed consideration of possibility to create megawatt-power lasers at buffer helium gas pressures up to 25 atm [9, 10].

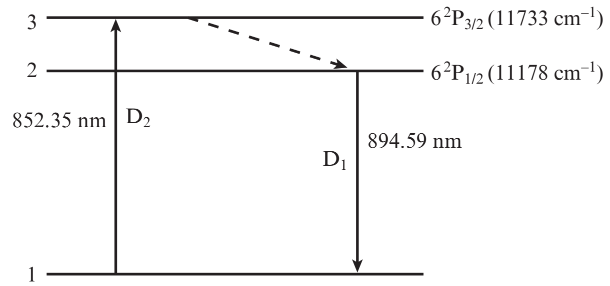

Figure 1. Energy-level diagram of caesium atom.

Early experiments on pumping by narrow-band radiation of solid-state lasers have demonstrated that the 'light-to-light' pump conversion efficiency may be as high as 63% [11]. For pumping with laser diodes the efficiency appeared to be somewhat lower, 61% [12]. The maximal power of diode-pumped lasers was 48 W (with 'light-to-light' conversion efficiency of ~49%) for a caesium vapour laser and 207 W (with 'light-to-light' conversion efficiency of ~9%) for a rubidium vapour laser [3, 13]. Up to now all experiments were carried out under the conditions in which the laser-active medium was placed into a closed volume of a few cubic centimetres, and the cooling of the medium was implemented via heat exchange between the medium and the cuvette walls. In the present paper for the first time the active medium circulation through the lasing region was used in alkali metal vapour lasers.

2. Setup description and experimental conditions

To pump the caesium laser we used narrow-band bars (1D-arrays) of diode lasers with external selective reflectors. The radiation divergence in two mutually perpendicular directions was corrected using aspherical microlenses. The laser diode bars were optically combined into a single case (unit). Each unit contained 15 bars. The emitting surface of the unit (emitting zone) was a 5×30 mm rectangle. Four laser bars units, placed in a horizontal plane, formed one pumping

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Received 3 October 2011; revision received 23 December 2011
Kvantovaya Elektronika **42** (2) 95–98 (2012)
Translated by V.L. Derbov

element, an array. The optical scheme of the arrays summing the radiation from four units in the horizontal plane provided the total emitting zone as large as 6×120 mm. The divergence of radiation was $\theta_x \sim 3$ mrad in the horizontal plane and $\theta_y \sim 0.1$ rad in the vertical plane. The system directing the radiation into the laser cuvette allowed the formation of a pump radiation region with the length $L \sim 36$ mm and the cross section ~5×4 mm^2 with the radiation power ~350 W on the laser cuvette window. To further increase the pump power, the principle of vertical summation of radiation from N arrays placed one over another (vertical periscope) was used. With such a pump system the emission zone was a ~(6N) × 120 mm rectangle, while the divergence remained the same ($\theta_x \sim 3$ mrad, $\theta_y \sim 0.1$ rad) independent of the number of arrays. The intensity of radiation (with no losses introduced by optical elements taken into account) was also the same both at the laser cuvette windows and inside the laser medium, because both the pump radiation power and the vertical beam size inside the laser cuvette were increased by the same N times.

The second similar source was placed at the opposite side of the laser cuvette (Fig. 2), which allowed experiments with both two-side and one-side pumping. The plane-parallel resonator was used, whose mirrors M1 and M2 having the reflection coefficients $R_1 = 0.35$ and $R_2 = 0.95$ and the output mirror M3 had the dimensions 5×15 mm and were placed within the pump radiation beam, causing its partial vignetting.

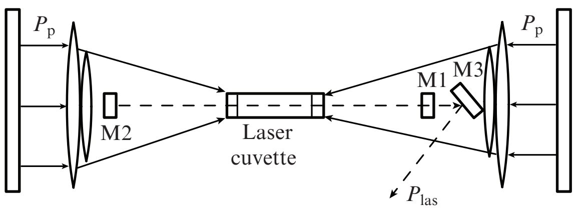

Figure 2. Schematic diagram of a diode-pumped caesium vapour laser.

The spectral width of particular laser diode bars at the half-maximum level was ~0.3 nm; however, in the experiments a shift of the emission line maxima with respect to the caesium absorption line was observed for individual bars, so that the spectral width of the radiation from all bars amounted to ~0.7 nm, ~90% of the total pump power being concentrated within the 1-nm-wide spectral interval.

The laser cuvette having the volume 12 cm^3 was incorporated in the closed double-loop system providing circulation of the laser-active medium through the pump beam (the total volume of the system being ~3000 cm^3). The main loop provided a continuous flow through the lasing zone with the velocity up to 20 m s^{-1}, while the additional loop provided a blow-off of the cuvette windows with the same velocity. The cuvette windows were made of sapphire and AR-coated. The transmission of the cuvette windows at the pump and lasing wavelengths was nearly the same and initially amounted to ~0.92. The construction was made of stainless steel and equipped with heating elements and temperature sensors. The temperature regime was maintained by means of an automatic thermal stabilisation system, so that the temperature of the windows was kept higher than that of metal constructions by ~10 °C.

To mix the upper caesium levels, we used methane instead of ethane, which allowed experiments at the temperatures of the laser medium up to 150 °C. At room temperature the pressure of the (He–CH_4–Cs) mixture varied from 1 to 5 atm, the partial pressure of methane being 0.1 – 1 atm.

3. Numerical modelling

To analyse the results and optimise the lasing conditions, a quasi-two-dimensional program was developed that allowed calculation of the lasing characteristics under the assumption that the pump and laser beams, propagating inside the laser cavity both to the right and to the left, possess a variable cross section that varies similar to that of a Gaussian beam in the vicinity of the waist:

$$S = S_w + \left[\pi \frac{\alpha}{2}(z - z_w)\right]^2, \qquad (1)$$

where S_w is the beam waist cross section; z_w is the waist position; α is the angle of the beam divergence at infinitely large distance from the waist.

Hence, the possible effect of the radiation intensity variation due to widening or narrowing of the beam is taken into account. It is assumed that the caustics of the pump and laser beams are coincident. The quasi-two-dimensionality consists in the fact that propagation of the pump and laser radiation beams along the z axis is calculated by means of direct integration of the transport equations, while the intensity variation due to the beam cross section changes is taken into account under the assumption that the intensity transverse distribution remains uniform. The characteristics of the input pump and laser beams may be set at the boundaries of the calculation interval of the z axis. Moreover, at the same boundaries the reflecting mirrors are introduced for both pump and laser radiation via the appropriate boundary conditions. Therefore, we can simulate the laser oscillation regime as well as the regime of amplification of externally injected signal. The active medium is confined by the windows, for which a given transmission coefficient is introduced.

The kinetic processes in the active medium, the pump radiation absorption, and the amplification of the laser radiation are described by the equations:

$$\frac{1}{c}\frac{\partial P_{las1}}{\partial t} + \frac{\partial P_{las1}}{\partial z} = \sigma_{21}(n_2 - n_1)P_{las1} - \gamma P_{las1} + k_{ns} S n_2,$$

$$\frac{1}{c}\frac{\partial P_{las2}}{\partial t} - \frac{\partial P_{las2}}{\partial z} = \sigma_{21}(n_2 - n_1)P_{las2} - \gamma P_{las2} + k_{ns} S n_2,$$

$$\frac{1}{c}\frac{\partial P_{p1}}{\partial t} + \frac{\partial P_{p1}}{\partial z} = \sigma_{13}\left(n_1 - \frac{1}{2}n_3\right)P_{p1},$$

$$\frac{1}{c}\frac{\partial P_{p2}}{\partial t} - \frac{\partial P_{p2}}{\partial z} = \sigma_{13}\left(n_1 - \frac{1}{2}n_3\right)P_{p2},$$

$$\frac{\partial n_1}{\partial t} = \sigma_{21}(n_2 - n_1)\frac{P_{las1} + P_{las2}}{S} \qquad (2)$$

$$- \int \sigma_{13}(\nu)\left(n_1 - \frac{1}{2}n_3\right)\frac{P_{p1}(\nu) + P_{p2}(\nu)}{S}d\nu,$$

$$\frac{\partial n_2}{\partial t} = -\sigma_{21}(n_2 - n_1)\frac{P_{las1} + P_{las2}}{S} - \frac{n_2}{\tau_2} + \gamma_{32}n_3 - \gamma_{23}n_2,$$

$$\frac{\partial n_3}{\partial t} = \int \sigma_{13}(\nu)\Big(n_1 - \frac{1}{2}n_3\Big)\frac{P_{p1}(\nu) + P_{p2}(\nu)}{S}\mathrm{d}\nu$$

$$-\frac{n_3}{\tau_3} - \gamma_{32}n_3 + \gamma_{23}n_2.$$

Here P_{las1}, P_{las2}, P_{p1}, P_{p2} are the powers for the laser and pump radiation waves, propagating to the right (subscript 1) and left (subscript 2); c is the speed of light; n_1, n_2 and n_3 are the populations of the energy levels $^2S_{1/2}$, $^2P_{1/2}$ and $^2P_{3/2}$ of the alkali metal atom, respectively; σ_{21} and σ_{13} are the cross sections of the corresponding transitions; $S(z)$ is the beam cross section at a given point inside the cavity; γ is the absorption coefficient of the active medium; γ_{32} and $\gamma_{23} = \gamma_{32}\times$ $\exp[-\Delta E/(kT)]$ are the rate constants of mixing of the upper sublevels; ΔE is the energy difference between the upper levels; τ_3 and τ_2 are the lifetimes for the spontaneous decay of levels 2 and 3; k_{ns} is the constant that determines the amplitude of the noise radiation and depends on the caustic geometry and expected lasing linewidth. The spectral and kinetic parameters of the active medium were taken from [9]. The integration of Eqns (2) was carried out in the spectral group approximation using the finite-difference method with the uniform mesh along the z axis. The time integration step Δt is related to the spatial mesh spacing Δz as $\Delta t = \Delta z/c$.

4. Experimental and computational results

Figures 3 and 4 show the laser radiation power versus the temperature of the cuvette walls and the gas medium pressure, obtained in the experiments with two-side pumping in 'single-decked' implementation with the transmission of the cuvette windows $\tau = \tau_1 = \tau_2 = 0.92$. The calculated results are also presented. Good agreement between the experimental and calculated data is observed.

Figure 5 shows the calculated dependences of the laser radiation power on the pump power at different transmissions τ of the cuvette windows together with the experimentally measured power values. One can see that the increase in τ, i.e., the decrease in intracavity losses, allowed essential improvement of the lasing efficiency and provided the laser radiation power of ~1 kW with the 'light-to-light' conversion efficiency ~48 %.

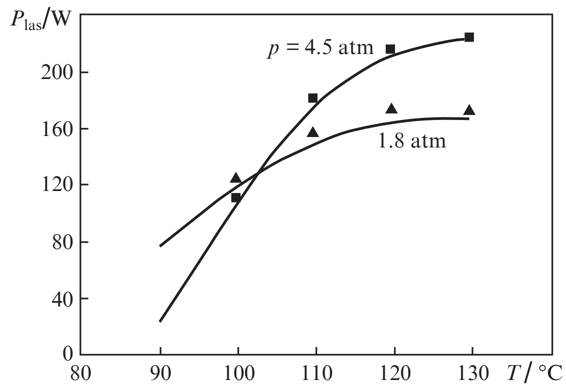

Figure 3. Calculated (solid curves) and experimental (dots) dependences of the laser radiation power P_{las} on the temperature T of the cuvette walls in the case of double-side pumping at P_p = 350 W from each side, L = 3.6 cm, and τ = 0.92. The calculation was performed at $\Delta\lambda$ = 0.7 nm, S_w = 0.2 cm^2, and α = 5°.

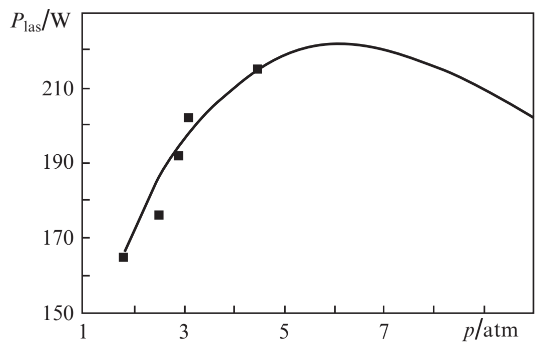

Figure 4. Calculated (solid curve) and experimental (dots) dependence of the laser radiation power P_{las} on the medium pressure p in the case of double-side pumping at P_p = 350 W from each side, L = 3.6 cm, τ = 0.92, and T = 120 °C. The calculation was performed at $\Delta\lambda$ = 0.7 nm, S_w = 0.2 cm^2, and α = 5°.

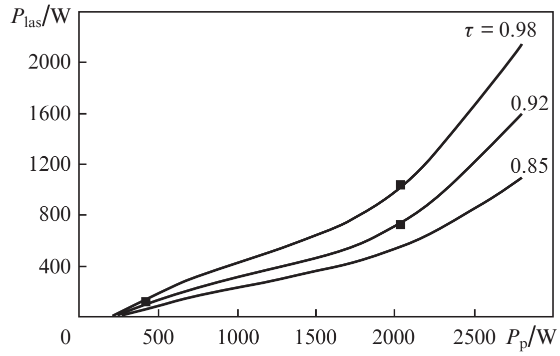

Figure 5. Calculated (solid curves) and experimental (dots) dependences of the laser radiation power P_{las} on the pump power P_p and the transmission of the cuvette windows τ at L = 3.6 cm and T = 120 °C. The calculation was performed at $\Delta\lambda$ = 0.7 nm, P_p/S_w = 3.5 kW cm^{-2}, and α = 5°.

5. Conclusions

The oscillation in a diode-pumped caesium vapour laser with active medium circulation is demonstrated for the first time. Under optimal conditions (the transmission of the cuvette windows 0.98) with double-side pumping (the pump radiation power 1 kW at each window), the power of cw laser radiation ~1 kW is obtained with the 'light-to-light' conversion efficiency ~48 %.

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