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Combined cw single-frequency ring dye/Ti : sapphire laser

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***Abstract*.** **A new combined cw single-frequency dye/Ti : sapphire laser with a ring resonator located in the horizontal plane and improved radiation frequency stability is developed. The short-term radiation linewidth does not exceed 10 kHz for the Ti : sapphire laser and is smaller than 100 kHz for the dye laser. The drift velocity of the emission line does not exceed 25 MHz h^{-1}. The scheme and design of the developed laser are presented which allow convenient switching of the laser between its solid-state and dye configurations.**

Keywords: *continuous-wave single-frequency ring laser, dye laser, Ti : sapphire laser, laser radiation frequency stabilisation.*

1. Introduction

Dye and Ti : sapphire lasers can be tuned in broad spectral ranges which are among the broadest ranges inherent in tunable lasers. The tuning ranges of these lasers are overlapped in the region between 700 and 800 nm. However, a Ti : sapphire laser is, as a rule, preferable for operating in the range above 700 nm as more efficient and simple for this wavelength range, while dye lasers are traditionally used in the region below 700 nm. The idea of the development of a combined tunable laser based on a Ti : sapphire laser and a dye laser is quite reasonable because such a laser can be tuned in a very broad spectral range from the visible to near-IR region.

The development of a combined tunable laser is especially expedient in the case of cw Ti : sapphire and dye lasers in which similar selecting elements and optical schemes are used (the active medium is located between two short-focus spherical mirrors, etc.). Another important argument in favour of the creation of a combined laser is that a Ti : sapphire laser and many dye lasers can be pumped by the same lasers.

Until now, only one combined cw single-frequency Ti : sapphire/dye ring laser was available (model 899, Coherent). The resonator of this laser was first used in a dye laser [1] and then in combined liquid – solid-state laser [2]. The main component of this laser design is a massive invar rod on which holders for all optical elements forming the vertical resonator of the laser are fixed. Most of the elements are located near the supporting invar rod; however, some of them are remote from the rod, which, of course, impairs the passive stability of the resonator. The emission linewidth of this laser in the frequency stabilisation regime is approximately 500 kHz and the drift velocity of the emission line does not exceed 50 MHz h^{-1} [3]. At the time of the development of this laser, more than two decades ago, these parameters were considered 'top-level'; however, at present even some commercial Ti : sapphire lasers emit lines of width smaller than 100 kHz [4, 5].

The aim of this work was the development of a combined cw single-mode Ti : sapphire/dye ring laser with improved emission parameters of lasers of both types. In this paper, we present the results of detailed experimental tests of this laser.

2. The laser design

The resonator of a combined laser is based on the scheme of a Ti : sapphire laser proposed in [6]. The specific feature and advantage of the ring resonator of this laser is the absence of the ultrafine quartz birefringent plate, which is commonly used together with a Faraday element in ring lasers [2, 4] to generate a single travelling wave. Optical rotation in the resonator described in [6] is performed by using a mirror located outside the resonator plane. In addition, the laser design makes it possible to obtain generation in a linear resonator, in particular, with all selecting elements and even a Faraday rotator, which is important for the preliminary optimisation of the adjustment of these elements.

The idea of realisation of a dye laser based on this scheme is to place a dye solution jet in the short arm of the resonator (see the resonator scheme in Fig. 1). A Ti : sapphire crystal is removed from the intermediate (in length) arm of the resonator, spherical mirror M1 of the Ti : sapphire laser resonator is replaced by a flat mirror (mirror M3 of the dye laser resonator) and plane mirror M3 of the Ti : sapphire laser resonator is replaced by a spherical mirror (mirror M1 of the dye laser resonator). In addition, spherical mirror M2 ($R = 100$ mm for the Ti : sapphire laser) is replaced by a spherical mirror with $R = 75$ mm and the pump beam is directed to the dye jet with auxiliary spherical mirror PM4. The positions of most optic holders in the combined laser do not change upon laser switching from one configuration to another (part I in Fig. 1).

Thus, the resonator is switched from the dye laser configuration to the Ti : sapphire laser configuration and

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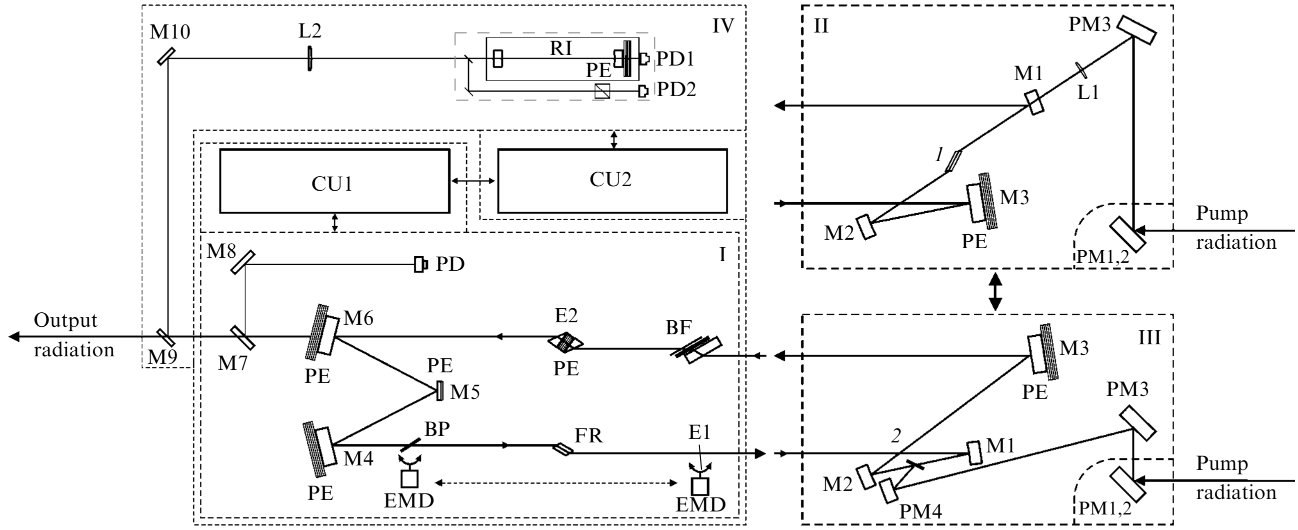

Figure 1. Scheme of the combined frequency-stabilised cw single-frequency ring dye/Ti : sapphire laser [I: part of the laser scheme used in both configurations of the combined laser; II: scheme of the Ti : sapphire laser used in the total configuration; III: scheme of the dye laser used in the total configuration; III: laser frequency stabilisation system using the reference interferometer (RI)]:
(CU1) electronic control unit of the laser; (CU2) electronic control unit of the laser frequency stabilisation system; (*1*) Ti : sapphire crystal; (*2*) dye jet; (PM1 – PM4) pump mirrors; (M1, M2) spherical laser resonator mirrors; (M3 – M6) flat laser resonator mirrors (mirror M5 is located outside the resonator plane); (BF) birefringent filter; (E1, E2) thin and thick Fabry – Perot etalons; (FR) Faraday rotator; (BP) Brewster plate; (EMD) electromechanical drive; (PE) piezoelectric element; (PD) photodetector of the laser control unit; (PD, PD2) photodetectors of the frequency stabilisation system; (L1, L2) lenses; (M7 – M10) auxiliary mirrors.

vice versa by replacing resonator mirrors and Faraday rotator and interchanging several optic holders. A birefringent filter and a thick etalon can be used in both configurations of the combined laser. This scheme is also convenient because the laser can operate in both configurations with the ring and linear resonators. The possibility of lasing in both configurations with the linear resonator (without mirror M5) considerably simplifiers the preliminary optimisation of the adjustment of the resonator and selectors. The electronic control systems and frequency stabilisation systems for both lasers are identical.

3. Vertical direction of the dye jet

The vertical direction of the dye jet restricts the distance h from the nozzle to the point where the jet touches the drain tube wall (Fig. 2). This distance should be minimal in the case of the vertically directed jet because the increase in h is in fact the increase in the jet height over an optical table and, hence, in the distance between the jet and the laser resonator plane. The latter impairs in the general case the stability of optical elements of the resonator. The typical problem appearing upon minimisation of the distance h is the frothing of the dye solution at the jet incidence site and its undesirable saturation with air bubbles. We solved this problem for a relatively small distance h (~ 90 mm) by finding the optimal conditions for the jet incidence on the drain tube wall. The minimisation of the angle α between the jet and tangent to the drain tube wall at the contact site of the jet with the tube wall (Fig. 2) and the restriction of the jet velocity by the value ~ 15 m s^{-1}, which is sufficient for highly efficient lasing at pump powers up to 10 W, eliminates the formation of air bubbles in the jet incident on the drain tube wall. In this case, the height H of the nozzle above the support plane of the laser was 110 – 115 mm.

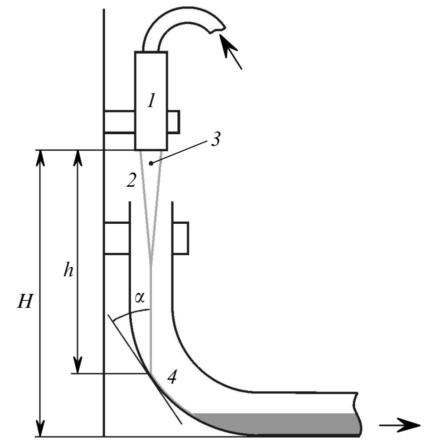

Figure 2. Geometry of the vertical dye solution jet in the laser: (*1*) nozzle; (*2*) dye jet; (*3*) point of incidence of the pump beam on the jet; (*4*) drain tube; (h) distance from the nozzle to the point of incidence of the dye jet on the drain tube; (H) height of the nozzle above the reference plane.

A comparatively small distance h can also cause additional oscillations of the jet resulting in an increase of the laser linewidth. However, as shown below, the vertical direction of the jet does not deteriorate the lasing stability; moreover, in the case of optimised parameters of the nozzle, such a laser can emit a narrower line compared to lasers using the horizontal dye jet.

4. Laser emission frequency stabilisation

The horizontal orientation of the resonator plane of the combined laser is also preferable for improving the passive frequency stabilisation (when the laser operates without the frequency stabilisation system). The laser linewidth in the free running mode does not exceed 5 MHz for the Ti : sapphire laser and 10 MHz for the dye laser.

The laser line is further narrowed by stabilising the emission frequency by the slope of the transmission peak of a temperature-controlled interferometer with a free spectral range of 750 MHz and a finesse of up to 400 (the typical width of the transmission peak slope of the interferometer was ~ 2 MHz). The interferometer was located near the laser and fixed on the optical table through vibration isolation rubber cushions.

The emission frequency of the combined laser is stabilised by using the fast and low feedback circuits. The working off bandwidth of the stabilisation system is ~ 100 kHz; an actuating element is a small mirror (M5) on a thin piezoelectric ceramics. The relatively broad working off bandwidth of the stabilisation system makes it possible to narrow the emission line of the Ti : sapphire laser down to ~ 20 kHz (similar laser linewidths were obtained in [7, 8]). In this case, the 2-kHz component caused by the modulation of the base of thick etalon E2 at the laser frequency dominates in the spectrum of residual perturbations of the laser frequency (this modulation is used in an automatic system for locking the transmission maximum of the thick etalon to the laser frequency). The laser linewidth smaller than 20 kHz was achieved by suppressing the residual 2-kHz modulation of the emission frequency of the Ti : sapphire laser with the help of an additional electronic circuit. The circuit feeds a weak out-of-phase signal at frequency 2 kHz (with controllable amplitude and phase) into piezoelectric elements of the resonator mirrors to compensate for this residual modulation, thereby narrowing the emission line of the Ti : sapphire laser down to ~ 10 kHz. The narrowest emission linewidth of the Ti : sapphire laser obtained in our experiments was 7 kHz.

The perturbation spectrum of dye laser frequency is broader due to the residual jitter of the dye jet, including high-frequency jitter, and therefore the dye laser linewidth is usually broader than that of the Ti : sapphire laser. In addition, the dye laser linewidth depends on the dye jet velocity. Figure 3 presents the experimental dependences of the linewidth and output power of the dye laser on the dye solution pressure at the nozzle entrance. The laser linewidth achieves the minimum root-mean-square value (about 80 kHz) at minimum solution pressure, whereas the laser output power increases with pressure. The optimum is achieved in the dye solution pressure range 1.5 – 1.6 atm (in this case, the dye jet velocity is 12 – 13 m s^{-1}) for the laser linewidth between 90 and 105 kHz and the output power 1.3 – 1.35 W. The dye laser linewidth is also quite sensitive to the nozzle design. Figure 4 shows the residual noise spectra of the dye laser frequency for a quartz nozzle with the output slit of size 3.5 mm × 0.25 mm and a sapphire nozzle with the slit of size 5 mm × 0.3 mm providing the dye jet velocity of 10 – 12 m s^{-1}. One can see that the residual noise spectrum in the laser with the quartz nozzle has a maximum in the region of perturbation frequencies 20 – 40 kHz, to which the stabilisation system responds weakly. As a result, the linewidth of the laser with this nozzle is 200 kHz. The linewidth of the laser with the sapphire nozzle under the same conditions does not exceed 100 kHz. In this case, the frequency dependence of the spectral density of perturbations of the emission frequency of this laser is flattened (Fig. 4b).

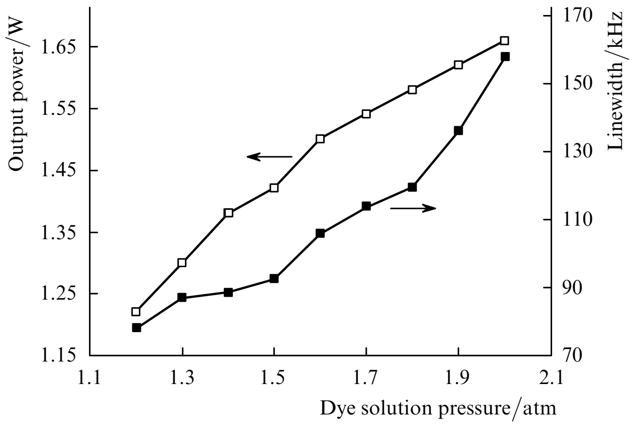

Figure 3. Dependences of the linewidth and output power of the dye laser on the dye solution pressure at the nozzle entrance.

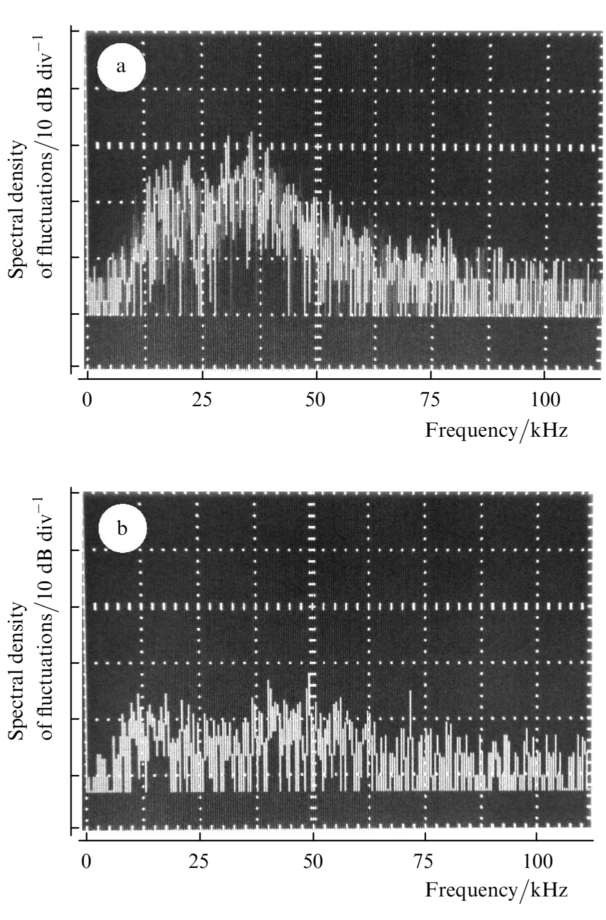

Figure 4. Density spectra of residual fluctuations of the emission frequency of the dye laser with a quartz nozzle with the output slit of size 3.5 mm × 0.25 mm (a) and a sapphire nozzle with the slit of size 5 mm × 0.3 mm (b).

The laser linewidths in the active frequency stabilisation regime were measured from residual error signals, which were recorded with a Fluke 189 multimeter with the function of measuring the true efficient values (True RMS) of signals of any shape within the frequency band 100 kHz. Note that error signals obtained in the standard scheme of stabilising the laser frequency by the slope of the transmission peak of a reference interferometer neglect the possible instability of the position of the transmission peak itself. Therefore, the linewidths presented here are relative (with respect to the reference interferometer), although we assume that the absolute laser linewidths weakly differ from the relative linewidths measured in our experiments because of a high vibration isolation of the reference interferometer achieved due to its independent disposition.

5. Long-term drift of the laser line

The long-term drift of the emission line of the combined laser in the frequency stabilisation regime was determined with a precision Angström WS/Ultimate wavemeter with a relative measurement accuracy 10^{-9} and temperature correction of measurements. The results of measurements of the drift velocity during 1.5 h for the Ti : sapphire laser presented in Fig. 5 demonstrate that the long-term drift of the laser line does not exceed 22 MHz h^{-1} and the drift can change its direction under real laboratory conditions (in the absence of thermostatic control).

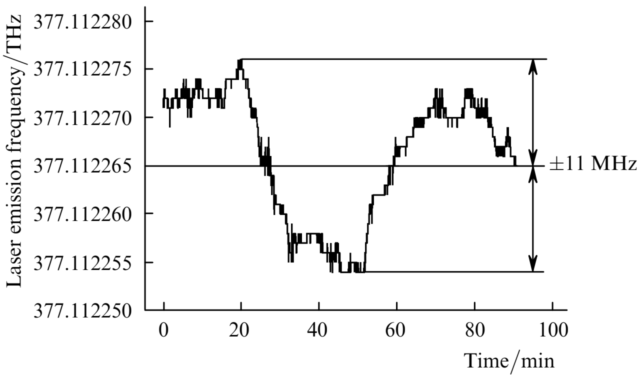

Figure 5. Time dependence of the laser emission frequency recorded with a WS/Ultimate wavemeter.

We also estimated the long-term drift of the emission line by tuning the laser line to the saturated absorption line of rubidium. This experiment gave the similar upper estimate 20 MHz h^{-1} for the long-term drift of the emission line of the frequency-stabilised laser.

The long-term drift of the emission line of the laser considered here is considerably smaller than that for its combined predecessor [2] because the reference interferometer developed by us was better thermostatically controlled. The base of this interferometer was varied only with the help of piezoelectric ceramics (one or several), and we did not use in it a Brewster plate with a drive, which can considerably deteriorate the thermal stability of the reference interferometer upon heating or cooling during operation.

6. Continuous laser frequency scan

The interferometer base was continuous scanned with the help of a mirror driven by a piezoelectric element. The scan region could achieve 18 GHz for the Ti : sapphire laser and 20 GHz for the dye laser. A similar continuous scan of the cavity was obtained by using a power-driven intracavity Brewster plate. The electromechanical drive was controlled by a signal proportional to the control signal of the piezoelectric element of the interferometer. The piezoelectric element of the interferometer and the Brewster plate of the laser resonator provided almost synchronous scan of the laser resonator and interferometer resonator without using the frequency stabilisation circuit. A small residual deviation from the synchronous scan (due to hysteresis of the piezoelectric element, etc.) is compensated by the laser frequency stabilisation system, which additionally synchronises the resonator length with the help of piezoelectric elements of the laser resonator mirrors.

7. Tuning properties of the combined laser

Figure 6 presents typical tuning curves of the combined single-frequency laser pumped by all the blue – green lines of an argon laser or by a 10-W solid-state laser emitting at 515 and 532 nm. The wavelength in the dye laser configuration can be tuned in the range from 545 to 770 nm by using four dyes. The tuning range of the Ti : sapphire laser is 695 – 1000 nm (by using five sets of mirrors). The combined laser can be tuned over the entire spectral range from 545 to 1000 nm by using a set of two three-component birefringent filters with tuning curves covering optimally this range [9].

Typical maximum output powers of the single-frequency combined laser for the most efficient dyes R6G and DCM in the region of the maximum gain of the Ti : sapphire crystal (about 800 nm) exceed 1.5 W for a pump power of 10 W. For the best samples of this crystal, the laser output power exceeds 2 W (Fig. 7).

In the wavelength range between 695 and 770 nm, the combined laser can operate both in the Ti : sapphire and dye laser configurations.

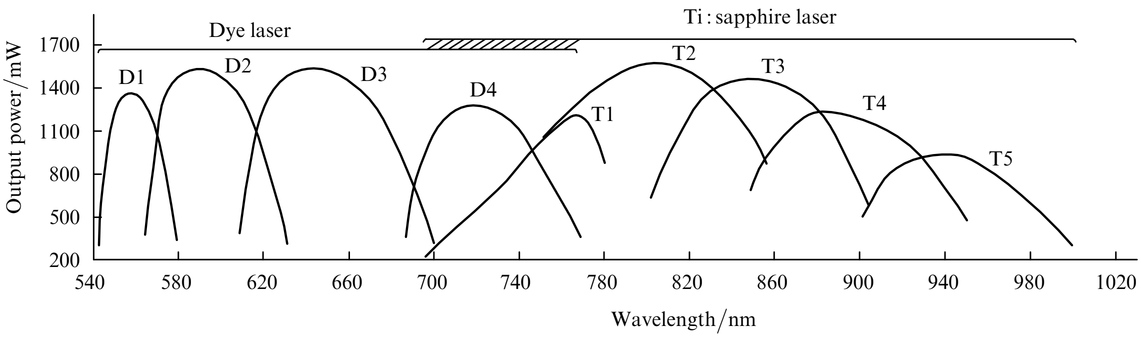

Figure 6. Tuning curves of the single-frequency combined laser for different dyes [rhodamine 110 (D1), rhodamine 6G (D2), DCM (D3), and pyridine 2 (D4)] and five mirror sets [T1 (695 – 780 nm), T2 (750 – 850 nm), T3 (800 – 900 nm), T4 (850 – 950 nm), and T5 (900 – 1000 nm)].

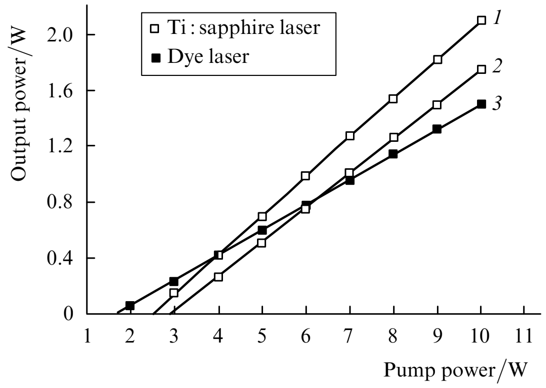

Figure 7. Dependences of the maximum output power of the combined laser on the pump power: (*1*) Ti : sapphire laser with the crystal and optics of the best quality; (*2*, *3*) typical lasers.

8. Conclusions

We have developed a combined single-frequency ring laser of the universal design based on a Ti : sapphire crystal and dye solutions. The horizontal orientation of the resonator realised for the first time in the combined laser improves the stability of optical elements and simplifies the use of the laser. The total tuning range of the laser is 550 – 1000 nm (550 – 700 nm for the dye laser and 695 – 1000 nm for the Ti : sapphire laser) for pumping at wavelengths 532 and 515 nm. The maximum output power is 2 W for the Ti : sapphire laser and above 1.5 W for the dye laser for a pump power of 10 W. The short-term linewidth without frequency stabilisation does not exceed 5 MHz (Ti : sapphire laser) and 10 MHz (dye laser). The short-term linewidth with the frequency stabilisation by using a specially developed thermostatically controlled reference high-Q interferometer is smaller than 10 kHz (Ti : sapphire laser) and smaller than 100 kHz (dye laser).

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