Ultra-narrow-linewidth combined CW Ti:Sapphire/Dye laser for atom cooling and high-precision spectroscopy

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ABSTRACT

Presented is a new combined CW Ti:Sapphire/Dye laser with horizontal output polarisation from a ring cavity and with improved stability of output frequency. Short-term output line width does not exceed 10 kHz for the Ti:Sapphire laser and amounts to 50 kHz for the Dye laser, output frequency drift being less than 30 MHz/hour, smooth scanning range is more than 19 GHz (Ti:Sapphire) and > 25 GHz (Dye). The maximum output power with a 10-W pump exceeds 2 W for the Ti:Sapphire configuration and is > 1.6 W for the dye one. The short-term line width without the frequency stabilisation is less than 5 MHz (Ti:Sapphire) and < 10 MHz (Dye); smooth scanning range without the frequency stabilisation is more than 47 GHz (Ti:Sapphire) and > 50 GHz (Dye). The total working spectral range of the combined laser stretches from 550 to 1000 nm (550–770 nm for the Dye and 695–1000 nm for Ti:Sapphire) when pumped with 532/515-nm radiation.

Keywords: Ti:Sapphire laser, Dye laser, single-frequency laser, tunable laser.

1. INTRODUCTION

Relevance of development of a combined tuneable laser on the basis of CW Ti:Sapphire and dye lasers is supported by the following factors:

- Wavelength tuning ranges of these lasers border each other (around 700 nm) and joining them into one large domain is particularly interesting for tasks which require broad-range spectral studies;
- The same sources in the blue-green range (diode pumped solid state lasers 532/515 nm, Ar lasers) can be used for pumping both CW Ti:Sapphire and CW dye lasers;
- CW Ti:Sapphire and CW dye lasers have very similar selective optical elements and feature analogous design approaches (*e.g.* active medium is placed between two short-focused spherical mirrors, etc.), electronic drive systems for these lasers are almost identical.

The idea to combine these lasers in one unit comes quite naturally and such laser is able to cover a considerable spectral range including visible and near IR domains.

2. HISTORY

The only version of combined tuneable laser based on CW Ti:Sapphire and CW dye lasers was developed by Coherent more than 20 years ago (the 899 series [1]). Optical resonator of this laser is vertically oriented, which is not the best arrangement for position stability of the optical cavity elements of this laser. Moreover, with the vertical resonator orientation it is necessary to position the dye jet horizontally, thereby creating additional problems with dye solution leaks when the system is turned on or shut down.

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3. COMBINED LASER WITH HORISONTAL ORIENTATION OF THE POLARISATION PLANE OF THE RESONATOR

This laser is built upon the resonator arrangement suggested in Ref. [2]. This configuration features a mirror set out of the resonator plane. A Faraday rotator in conjunction with this mirror ensures that only one travelling wave exists in the cavity. This mirror set outside the plane of the laser cavity performs a slight turn of the beam polarisation plane, which is necessary to compensate the angle introduced by the Faraday rotator. Besides this, the configuration of such laser readily allows linear generation mode in the resonator with all the selective elements in place and even the Faraday rotator in the beam path, which is very important for preliminary alignment of these elements.

The main idea of dye laser on the basis of this configuration is to place the dye jet in the shortest arm of the cavity (see the resonator schematic in Fig. 1). The Ti:Sapphire crystal is removed from the mid-length resonator arm, spherical mirror M1 of the Ti:Sapphire laser is changed to a flat one (mirror M3 of the dye laser cavity) and flat mirror M3 of the Ti:Sapphire resonator is exchanged for a spherical one (mirror M1 or the dye laser cavity). Additionally, spherical mirror M2 (R = 100 mm for the Ti:Sapphire laser) is removed and a spherical mirror with R = 75 mm is inserted in its place, the pumping beam is guided into the dye jet with the help of extra spherical mirror M_{P4}. The majority of optical element mounts of the combined laser remains keep their positions unchanged (part A in Fig. 1) and when the Ti:Sapphire configuration is changed into the dye one and *vice versa*.

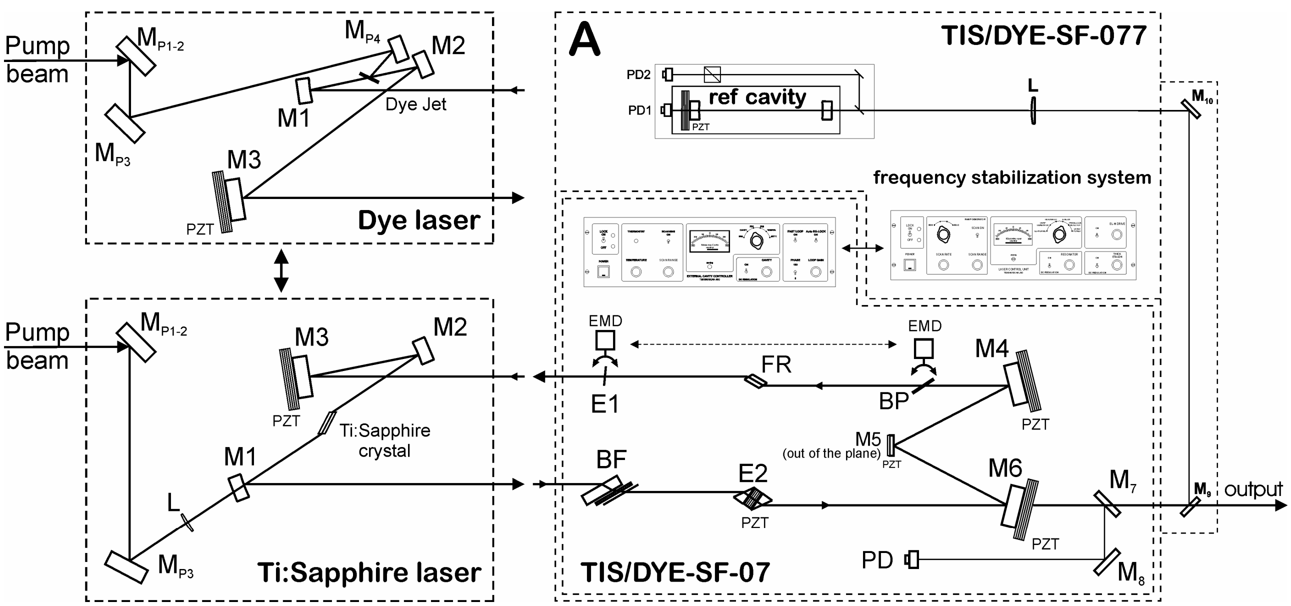

Fig. 1. Layout of the combined CW ring single-frequency Ti:Sapphire/Dye laser: M_{P1-4} - pump mirrors, M1 & M2 - spherical mirrors (R=75 mm for Dye laser and R=100 mm for Ti:Sapphire laser), M3, M4 - flat mirrors, M5 - small-mirror/fast-PZT assembly, M6 - output mirror, BF - 3-plate birefringent filter, E1 – solid thin Fabri-Perot etalon, E2 - thick Fabri-Perot etalon, FR - Faraday rotator, BP - Brewster plate, PD - photodetector, L - lens, M7-M10 - auxiliary mirrors, PZT – piezoceramic, EMD – electro-mechanical drive.

Therefore, switching of the resonant cavity from the dye jet configuration into the Ti:Sapphire one or the other way around is done by changing of resonator mirrors, Faraday rotator, and repositioning of several optical elements, the birefringent filter and the thick étalon can be used in both configurations of the combined laser. The suggested arrangement of the combined laser [3] provides additional convenience: in both configurations the laser can operate both with a ring and a linear cavity. The possibility of operation of both lasers in a linear configuration (without mirror M5) considerably simplifies alignment of the cavity and selective elements. Electronic control systems and the frequency stabilisation system are identical for these two laser configurations.

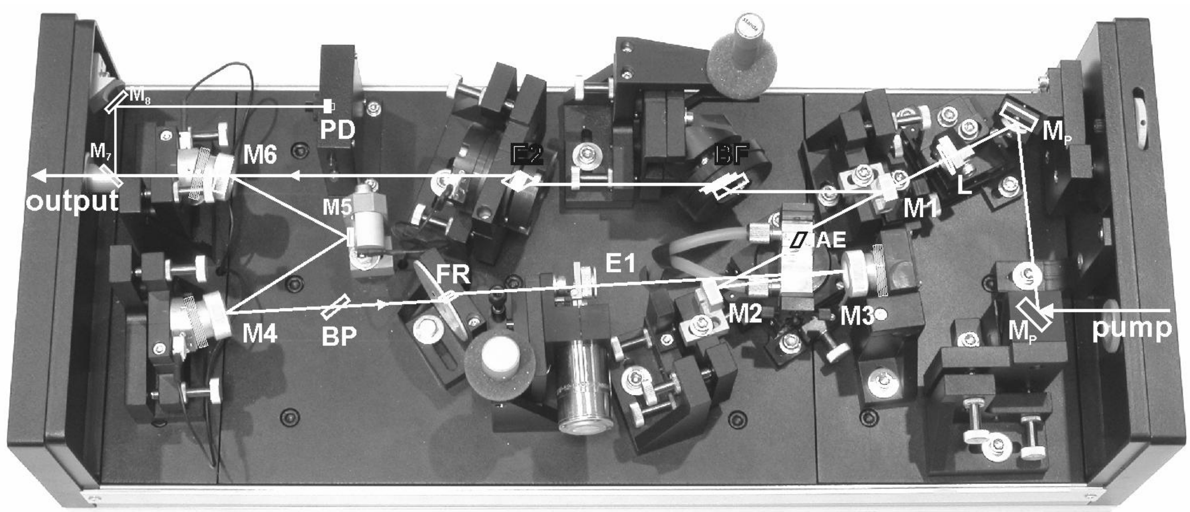

Fig. 2. Layout and top view of combined CW single-frequency ring laser in Ti:Sapphire laser configuration: M_P - pump mirror, L - lens, M1 & M2 - spherical mirrors, M3, M4, M5 - flat mirrors, M6 - flat output mirror AE - Ti:Sapphire crystal, BF - 3-plate birefringent filter, E1 - thin Fabri-Perot etalon, E2 - thick Fabri-Perot etalon, FR - Faraday rotator, PD - photodetector, M7 & M8 - auxiliary mirrors.

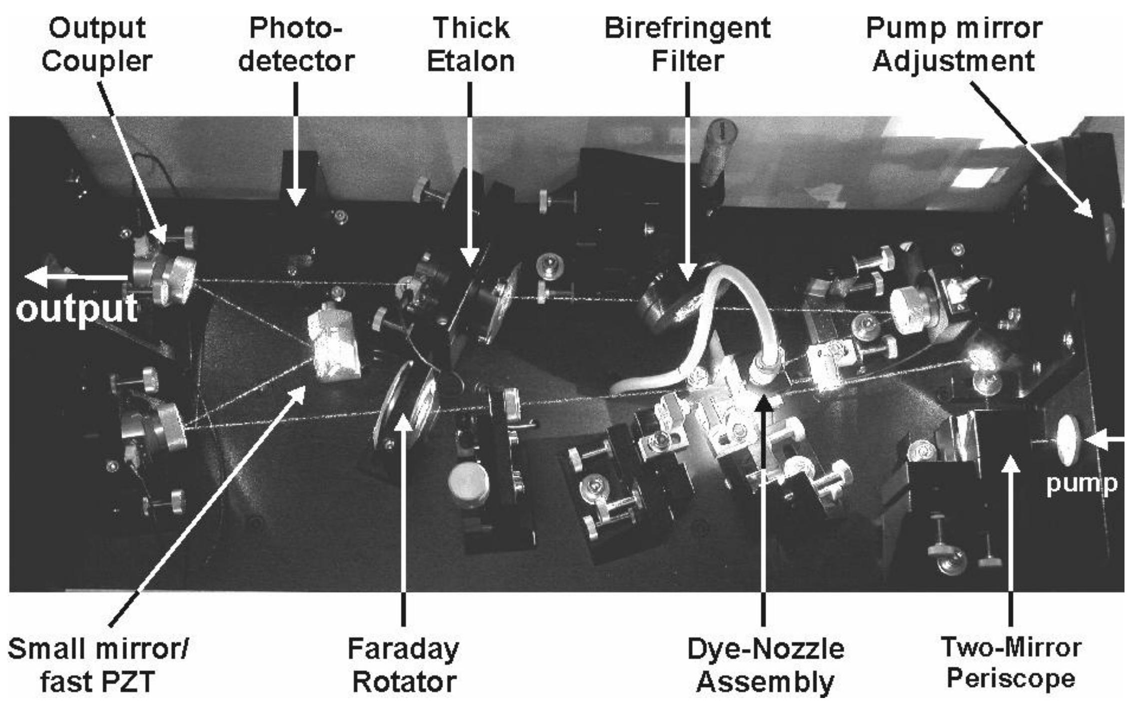

Fig. 3. Top view of combined CW single-frequency ring laser in Dye laser configuration: a picture is given of the laser in operation, real beams of the dye laser and the pumping laser are visible.

4. STABILISATION OF LASER RADIATION FREQUENCY BY A REFERENCE INTERFEROMETER

In the free-running generation mode the laser radiation has a line width of not more than 5 MHz for the Ti:Sapphire laser and no more than 10 MHz for the dye laser. Depending on the ambient conditions, the long-term radiation line drift for both lasers in the free-running mode may be 300–500 MHz/hour and more.

Further reduction of the line width of the laser is performed with a frequency stabilisation system that locks onto a slope of transmission peak of a thermo-stabilised interferometer that has free dispersion range of 750 MHz and spectral finesse of up to 400 (typical width of the transmission peak slope of such interferometer amounts to about 2 MHz). The reference interferometer is positioned beside the laser on a single optical bench to which it is attached through a vibration sink platform. The interferometer allows for smooth scanning of the laser output frequency in the stabilised mode of the Ti:Sapphire configuration within > 19 GHz and within > 25 GHz in the stabilised dye laser configuration

Stabilisation of the radiation frequency of the combined laser is performed by two control loops - the fast and the slow one. The slow control loop is actuated by PZT elements of mirrors M4–M6 of the laser cavity, the fast loop is actuated by a special thin PZT of mirror M5. The band-width of the frequency stabilisation system reaches up to 100 kHz, the actuated element being small mirror (M5) attached to a thin PZT element. Relatively broad frequency band-width of the stabilisation system allows effectively to narrow the generation line of the Ti:Sapphire laser down to 7 kHz. High thermal and position stability of the reference interferometer leads to a reduction of long-term frequency drift of the laser down to 30 MHz/hour and less (Fig. 4). Relatively small long-term drift of the laser radiation line was achieved due to the absence in the reference interferometer of the traditional galvanometer actuator of the Brewster plate that has a negative impact on the interferometer temperature stability.

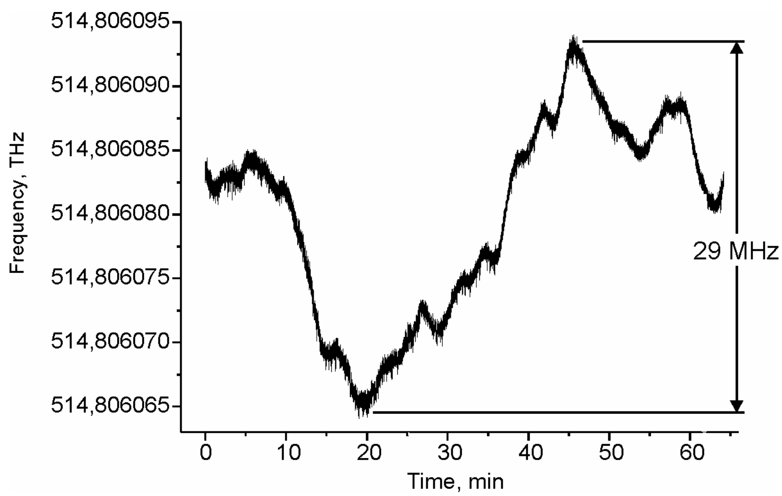

Fig. 4. Dependence of laser frequency on time obtained with wavelength meter WS/Ultimate.

The output of the dye laser is affected by a broader spectrum of perturbations originating from residual jitter of the dye jet (including high-frequency one), this is why normally the line width of the dye laser radiation exceeds that of the Ti:Sapphire laser. It was especially interesting to compare line-widths of output from both lasers in case they share the same resonator design, the reference interferometer, and also the same electronic control units. The narrowest radiation line width of the dye laser amounted to 50 kHz when pumped by a diode pumped solid-state laser (Verdi-V10); when pumped by an Ar laser the line width was about 90 кHz. Narrower line width of the dye laser output when pumped by Verdi was observed because this pump source exhibits considerably smaller output power fluctuations as compared to an

Ar laser. In Fig. 5 the frequency dependence of the spectral density of perturbations in the dye laser generation frequency is given for the radiation line width of 75 kHz. Sharp peak at 2 kHz corresponds to 2-kHz modulation of automatic adjustment system of the single-frequency mode of the laser.

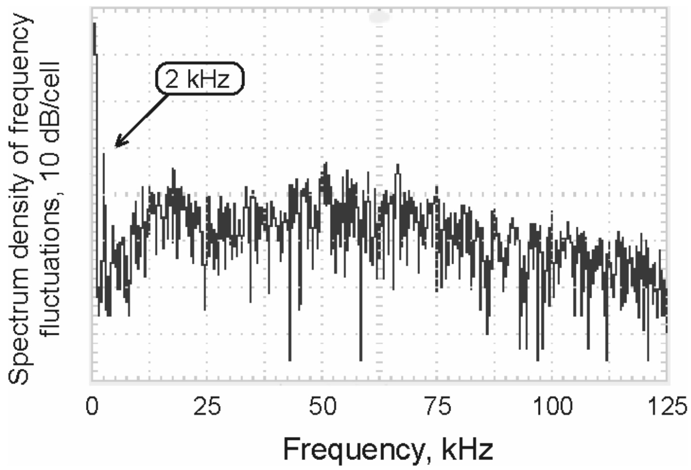

Fig. 5. Spectral density of the frequency noise of the stabilized laser in Dye configuration, linewidth: 75 kHz rms.

Specified line width values for the laser with active output frequency stabilisation have been measured by residual error signals registered by a Fluke 189 multimeter that has true RMS feature for signals of any shape within a 100-kHz frequency range. It is necessary to note that error signals observed in the standard scheme of laser frequency stabilisation by the slope of transmission peak of the reference interferometer do not include the possible instability of the position of the transmission peak itself. This is why the stated line widths are relative to the reference interferometer, however we believe that the absolute widths of laser radiation lines differ little from the relative values we measured because of perfect vibro-isolation of the reference interferometer, which is possible due to its independent placement.

5. EXTENSION OF SMOOTH FREQUENCY TUNING RANGE

The basic smooth frequency detuning range of the combined laser is defined by the maximum mirrors travel that is provided by three PZT elements. This range exceeds 5 GHz in the configuration of Ti:Sapphire laser and amounts to more than 6 GHz for the dye laser. Modulation of the output power of the laser over the maximum possible generation frequency detuning with the help of these three PZT's is less than 3% and is mainly caused by slight change of angular positions of the mirrors when they are actuated by PZT's. Extension of the smooth frequency detuning range is possible in the combined laser by insertion of a single inclinable Brewster plate. Normally, when this method is used two plates are used, which are inclined in opposite directions, thereby ensuring unchanged beam position in the resonator. Obviously, when the plates are at an angle different from the Brewster one there are additional losses in the cavity and consequent output power modulation. In our combined laser, for extension of the smooth frequency detuning range in both configurations a single Brewster plate is used, which is inclined with an electro-mechanical actuator. Depending on the thickness of this plate, the smooth frequency detuning range of the laser may be extended to 30–50 GHz. In Fig. 6 the dependence of the laser generation frequency in the Ti:Sapphire configuration upon time during automatic smooth frequency scanning is given when a 10-mm thick Brewster plate is used. The entire range of smooth detuning amounts to 47 GHz and has two components: the 5-GHz range provided by the three PZT elements and the 42-GHz range provided by the inclined Brewster plate. Total modulation of the output power of the laser over the full 47-GHz range of smooth frequency scanning did not exceed 10%. With a thinner Brewster plate, let's say 7 mm, the smooth frequency detuning range is around 30 GHz and the modulation of the output power over this range are less than 8%.

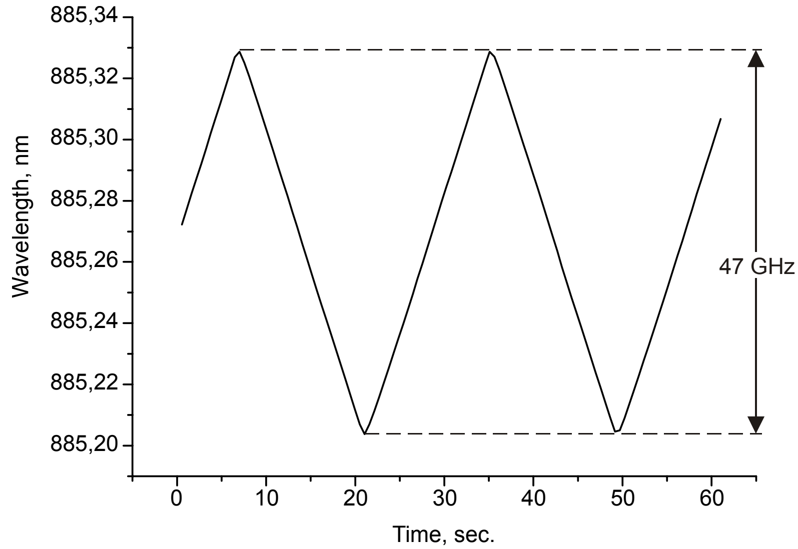

Fig. 6. Automatic smooth scanning of Ti:Sapphire laser frequency in the free-running generation mode (regime of passive frequency stabilisation).

When frequency is continuously scanned with the frequency stabilisation system (by reference interferometer) active the widest scanning range is determined by the maximum possible adjustment of the reference interferometer base. The base of the interferometer we developed is adjusted with two PZT elements that produce the maximum detuning of the interferometer transmission peaks within ~ 25 GHz in the dye laser generation domain (Fig. 7) and within ~19 GHz for the Ti:Sapphire radiation. Correspondingly, the largest possible smooth frequency detuning range with the frequency stabilisation system active is limited by these figures (25/19 GHz).

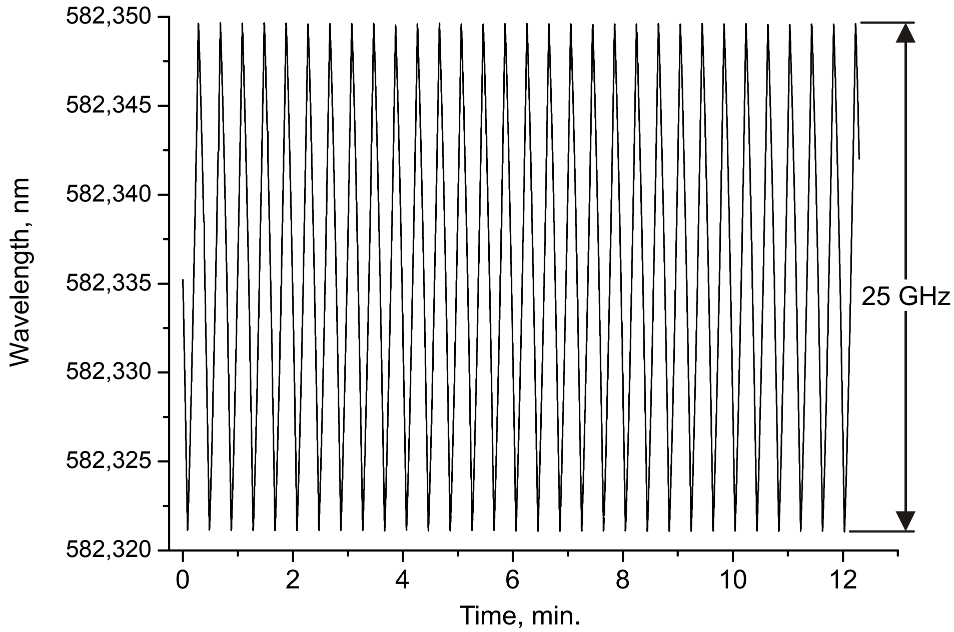

Fig. 7. Automatic smooth scanning of Dye laser frequency in regime of active frequency stabilisation.

6. FREQUENCY STABILISATION SYSTEM WITH AUTO-RELOCK FUNCTION

It is evident that due to the narrow transmission peak of the reference interferometer and the conventional frequency stabilisation on the slope of this peak the system may go out of lock when rapid jumps in laser generation frequency by more than the width of the transmission peak slope occur. In such cases the system tries to find the "lost" transmission peak. As a result, the PZT elements of the slow and fast control loops may receive maximal drive voltages, and if the system still cannot find the transmission peak it enters a non-operational state with maximal (minimal) drive voltages on the actuators. The conventional way of restoring the system operation in this case is to switch the frequency stabilisation off and on again. It is in this manner that users of analogous stabilisation systems proceed when the laser frequency jumps off the slope of the interferometer transmission peak. The Auto-Relock function implements a different approach. When this function is active the system keeps track of the control voltages on the actuators and, as these voltages reach the limit, it automatically decrements (or, correspondingly, increments) this control voltage until the laser generation frequency returns back onto the slope of the interferometer transmission peak. Further, the laser frequency is automatically locked by the stabilisation system (Fig. 8).

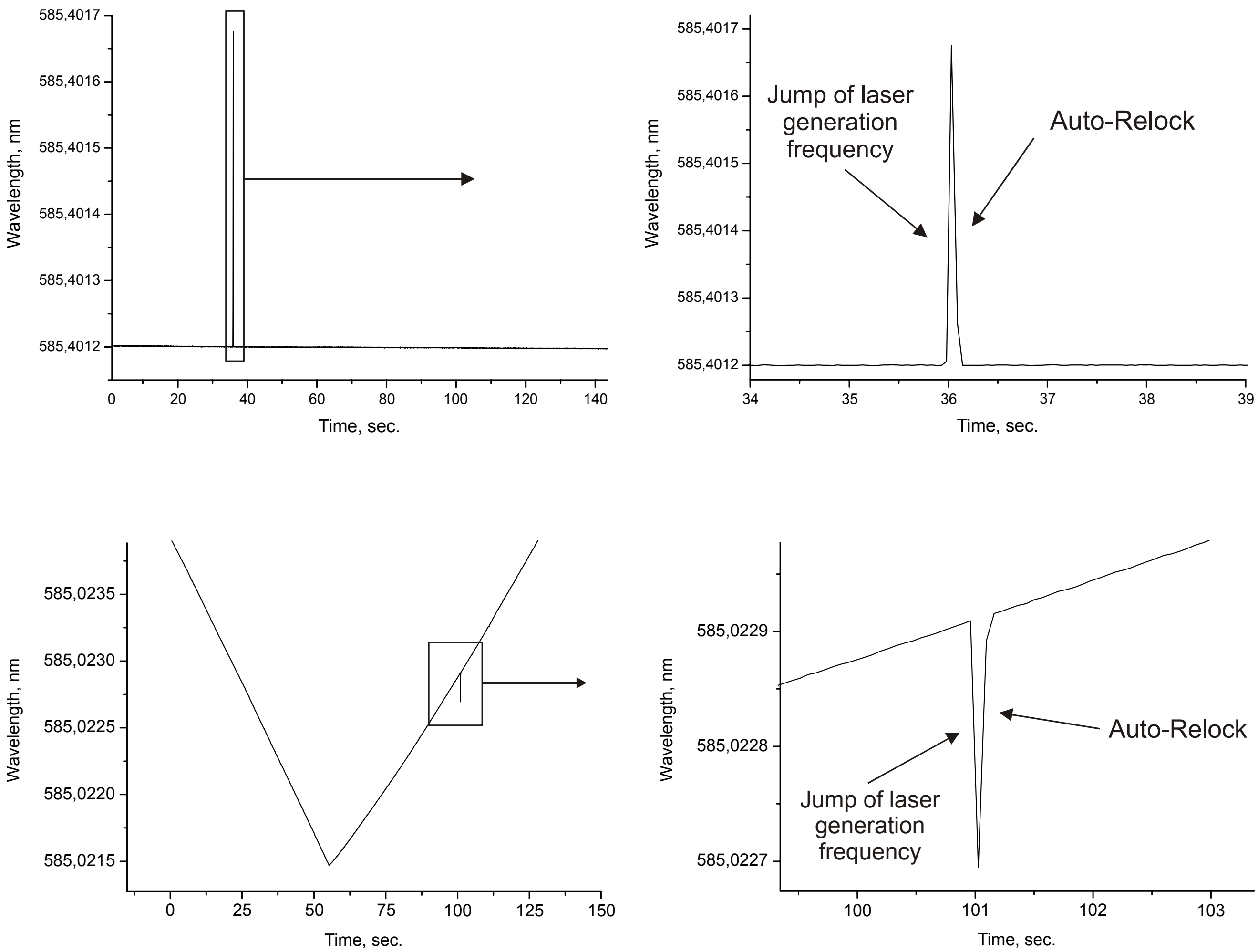

Fig. 8. Demonstration of Auto-relock function work in regime of fixed wavelength and in regime of automatic smooth scanning of Dye laser frequency.

7. SUMMARY

In this paper we present the results of development of a combined single-frequency ring laser with universal design that allows efficient use of both Ti:Sapphire crystal and a dye jet as the active medium of the laser. For the first time such combined laser design was implemented in a horizontal resonator scheme, thereby providing improved position stability of optical elements and added convenience of use. The total working spectral range of this laser amounts to 550–1000 nm (550–700 for the dye laser and 695–1000 for the Ti:Sapphire laser) when pumped with a 532/515-nm source. Maximum output power of the laser with a 10-W pump exceeds 2 W for the Ti:Sapphire laser and 1.5 W for the dye laser. The short-term line width without the frequency stabilisation is less than 5 MHz (Ti:Sapphire) and < 10 MHz (dye laser). With the frequency stabilisation on a special high-finesse reference interferometer with thermostabilisation the line width is reduced to less than 10 kHz (Ti:Sapphire лазер) and down to ~ 50 kHz (dye laser).

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