Single-frequency stabilized dye jet laser pumped with a Cu-vapour laser through a fibre

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ABSTRACT

Presented is a stable single-frequency master-oscillator on the basis of a pulsed dye jet laser for powerful isotope separation systems. In a simple GIG resonator without prism expanders, we obtained 170-mW single-frequency output power with an open beam pump and up to 100 mW with a fibre-guided pump. The application of a frequency stabilization system brought the short-term stability down to 50 MHz/s (at pulse duration 8 ns, 15-kHz repetition rate) and the long-term stability down to 120 MHz/hour. A smooth frequency scan within an 8 GHz region (and wider) was achieved on the basis of pivot method with newly implemented components.

Keywords: pulsed dye laser, single-frequency, GIG-resonator, smooth frequency scan

A single-frequency dye laser (SF-DL) pumped with a Cu-vapour laser (CVL) is an efficient source of tunable narrowband radiation of the visible spectrum. An important field of application of this type of lasers is that of using them as master oscillators in powerful laser isotope separation systems. The spectral characteristics of the output radiation of these systems is largely determined by those of the master oscillator. This refers to the radiation spectrum width, the radiation frequency stability, and the smooth scanning range of the frequency. The works aimed at developing and applying new methods of improving the spectral characteristics of master oscillators on the basis of SF-DL pumped with a CVL are rather numerous [1], but, to our view, the ways of improving this kind of lasers are far from exhausted.

In this paper we present a stable single-frequency dye jet laser pumped with a CVL through a light guide designed to be used as a master oscillator of a powerful laser system [2]. In designing the laser at issue particular attention has been given to improving the short-term and the long-term frequency stability, developing simpler methods of smooth frequency tuning, and to optimizing the delivery of pump radiation into the active medium.

In the designed dye laser use has been made of a GIG-type resonator (a short resonator with a grazing incidence of radiation onto a diffraction grating) with the dye cell replaced by a free-flowing dye jet (fig. 1). Longitudinal pumping was employed, the pump radiation is made through a dichroic mirror of the resonator with 89 % of the CVL green line being passed. The selecting element was a holographic diffraction grating produced by the firm "American Holographic" (2400 rulings/mm, 50 mm long) fixed at an angle of $89^{o}30'$ to the resonator axis. The flow rate of the dye solution was 10 m/s, the jet cross-section is 0.5 mm x 4 mm (the jet former is a quartz nozzle), the incline of the jet to the resonator axis is 10^{o}. The laser dye solution used was 1.3×10^{-3} M/liter Rhodamine 6G in a ethylene glycol - pure alcohol mixture (1:1). The tuning mirror was a high reflectivity dielectric coated optical flat. The duration of the SF-DL oscillation pulses did not exceed 8 ns FWHM, the duration of the CVL pulses was 12 ns FWHM, the pulse repetition rate was 15 kHz.

The dye jet laser could be pumped both with an open Cu-laser beam and through a light guide . The open beam of the CVL was focused in the dye jet laser active medium by means of a lens with 65-mm focal distance, the pumping beam waist diameter amounting to about 100 μm. Fig. 2a presents the measured pumping beam waist profile for this focusing, the measurement was made with a one dimensional photodiode array (the distance between the array elements was 25 μm).

For the 3.5 W power of the pump radiation (CVL green line) fed into the dye solution jet, the output power of the dye laser amounted to 170 mW in stable single-mode operation with the maximum output power of about 565 – 570 nm. The maximum overall efficiency of pump radiation conversion was 4.6%. It should be noted that in the short-resonator GIG laser this parameter is largely determined by the diffraction grating efficiency and that for the most efficient gratings the overall pump radiation conversion efficiency can reach 12% [3] while the typical values of the overall efficiency for GIG-dye-lasers fall within the range of 4 – 6%. A significant increase in the efficiency of a SF-DL can be expected in using combined gratings [4], their production, however, is so far connected with a number of technological problems.

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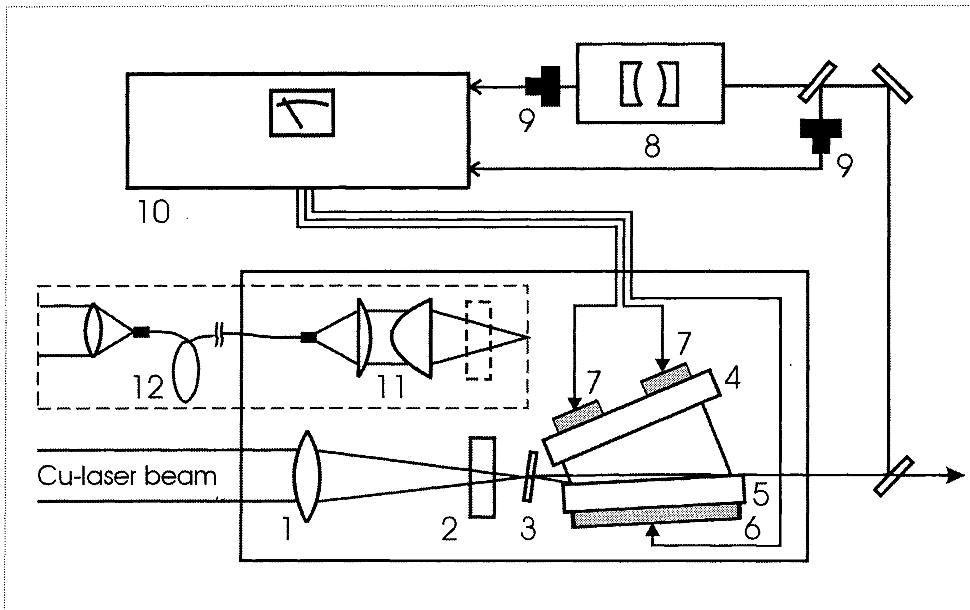

Figure 1. The schematic of the designed single-frequency dye jet laser: 1 – focusing lens, 2 - dichroic mirror of the resonator, 3 - dye solution jet, 4 - tuning mirror, 5 - holographic diffraction grating, 6 - auxiliary piezoelectric element, 7 – control piezotransducers, 8 - reference confocal interferometer, 9 – photodetectors, 10 – SF-DL electronic control unit, 11 - modified Fraunhofer objective, 12 - light guide.

The application of a fiber for delivering the pumping laser beam into the GIG-dye-laser active medium which was first accomplished in reference [5] under the conditions of longitudinal pumping makes it possible to spatially "untie" these lasers and improve the stability of the frequency and power characteristics of dye lasers. The main problem arising in using a light guide consists in obtaining a sufficiently small waist of the pump beam at the exit of the light guide. In focusing the light guide leaving beam with a spherical lens the beam waist diameter is close to that of the light guide diameter. However, the application of a light guide with a relatively small diameter, say, with that of 100 μm, creates problems in feeding a relatively powerful pump beam due to the destruction or welding off of the light guide inlet end.

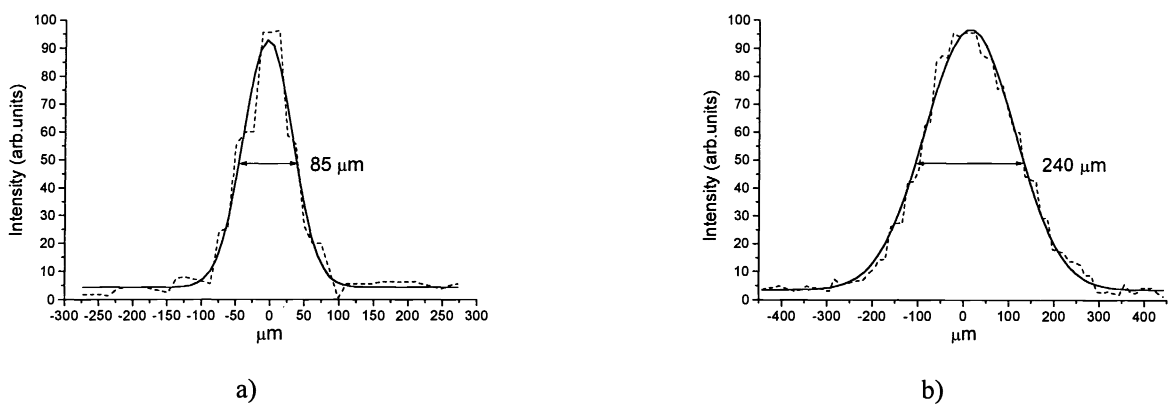

Figure 2. The measured pump beam waist profile in focusing; (a) an open beam with a spherical lens, (b) a beam at the light guide outlet with a modified Fraunhofer objective; (the dotted line denotes the experimental data, the solid line shows the approximation with a Gauss contour).

To deliver the pumping laser beam to the dye jet laser, we used a light guide of the quartz-quartz type with an inner diameter of 400 μm. The pump beam was focused into the fiber by means of a spherical lens with a 65-mm focal length. The radiation losses in passing through the light guide did not exceed 14%. To focus the pump beam at the exit of the light guide we used a modified Fraunhofer objective with a 40-mm focal length consisting of a planoconvex and a parabolic lenses. This objective introduces relatively small spherical aberrations and makes it possible to concentrate up to 90 – 95% of the radiation in the light spot of an essentially smaller size than that of the light guide diameter. The least pump beam waist diameter obtained in the dye solution jet was that of 240 μm (Fig. 2b).

In pumping a dye jet laser through the light guide the pump power getting into the dye solution jet was equal to 2 W (510.6 nm), that of the output of the dye jet laser in single-frequency operation amounting to 80 mW (the overall exitation conversion efficiency amounts to 4%). Thus, the improved pump beam focusing at the 400 μm light guide outlet by means of a modified Fraunhofer objective makes it possible to obtain a single-frequency oscillation regime in a dye jet laser with a GIG-resonator without using any prism beam expanders and with the relatively high pump power conversion efficiency.

The short-term (for averaging times of 1 sec) dye jet laser oscillation frequency free-running jitter controled with the help of a scanning Fabri-Perot interferometer with a resolution of 30 MHz amounted to 100 – 150 MHz/sec. The external conditions of the laser service worsening (vibration, acoustic disturbances), the short-term oscillation frequency jitter could increase up to 500 – 600 MHz. Note that the range of the short-term free-running frequency jitter in similar short-resonator GIG-dye-lasers lies between 100 – 150 MHz [3] and 1 GHz [6], sometimes even more.

Systems of active stabilization of frequency generation in a dye laser pumped with a CVL are used quite seldom, and their arrangement is quite diverse. Frequency generation can be actively stabilized with the aid of a high-precision wavelength meter [7, 8], a two-element photodetector recording the change in the angular position of the output beam with changing oscillation frequency [9, 10], a reference interferometer recording the passing radiation by a linear CCD array with subsequent digital data processing [11] or a scanning reference interferometer with the digital processing of its registered passage profile [12]. Characteristic of most systems applied to actively stabilize the SF-DL is computer-based data processing as well as computer-aided elaboration of the finalizing control signal. Since the limited speed of the digital systems of the active stabilization of a pulse dye laser frequency does not permit the short-term frequency stability to be essentially improved, their application is mainly aimed at decreasing the laser's long-term frequency generation drift.

To stabilize the dye jet laser's oscillation frequency, we used the method of the frequency lock to a side of a transmission fringe of the reference cavity with an analog feedback loop control system. The reference interferometer represented a thermostatically controlled confocal Fabri-Perot interferometer (the temperature instability of the interferometer is < 0.02°) with a FSR 5 GHz, finesse 2. An actuating element of the frequency stabilization system were the piezotransducers of the tuning mirror. The response time of the feedback loop control system was 0.1 sec. The application of the frequency stabilization system made it possible to reduce the short-term oscillation frequency jitter of the dye jet laser down to 50 MHz/sec (fig. 3) an to achieve the long-term stability of the oscillation frequency of 120 MHz/ hour. Obtained short-term linewidth is of the order of the Fourier transform limit for a 8 ns laser pulse.

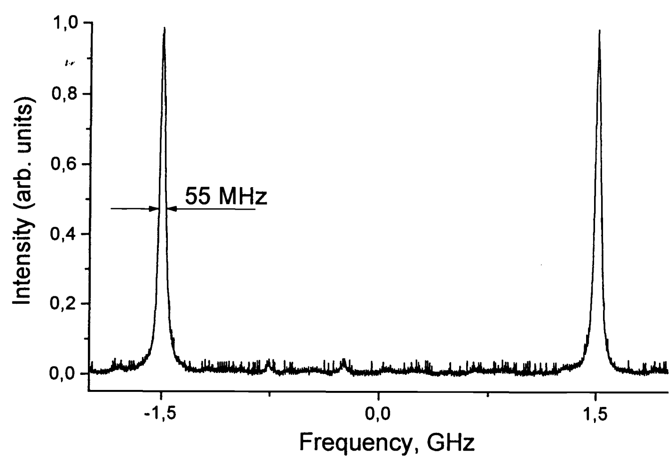

Figure 3. Single-mode stabilized dye laser output monitored by a 3 GHz FSR scanning confocal interferometer (finesse=100). Approximately $5 \cdot 10^3$ laser pulses occurred during the sweep.

The traditional method of smooth single-frequency scanning in GIG-resonators is the pivot-method [13, 14]. The gist of the method consists in that to smoothly scan the oscillation frequency of a short-resonator GIG-laser in a range exceeding that of resonator dispersion, the tuning mirror turns around a certain axis referred to as a pivot-axis. The location of this axis is determined by an intersection of the plane of the tuning mirror and that of the diffraction grating. This rotation of the tuning mirror synchronizes the rates of scan the frequency of the resonator's selected longitudinal mode and of the maximum reflection of the diffraction grating. The other method of the smooth frequency scanning in the laser with a GIG-resonator involves the application of an additional optical element: a wedge located between the diffraction grating and the rotary mirror [15, 16]. In this case the rates of scan the resonator's selected longitudinal mode frequency and the maximum reflection of the diffraction grating are synchronized when the wedge also rotates around a definitely located axis. However, the successful application of these methods to smoothly scan the oscillation frequency of a GIG-laser is rather a complicated task as it requires a high-precision actuating mechanism (say, a high-precision kinematic drive) and sufficiently accurate adjustment of the frequency scan unit.

To simplify the procedure of the smooth oscillation frequency scanning in a dye jet laser with a GIG-resonator we combined the idea of the pivot method with a new and simpler actuating mechanism of the tuning mirror rotation. For a prescribed rotation of the GIG-resonator's tuning mirror we used two piezoelectric transducers with a very simple control scheme.

If the tuning mirror of a GIG resonator is mounted on two identical piezoactuators placed at a distance $2L$ from each other (fig. 4), then for the mirror to turn through $\delta\varphi$ round the pivot-axis, the ration of the voltages fed to the piezoactuators must be equal to

$$\frac{U_2}{U_1} = \frac{h_2}{h_1} \approx \frac{d+L}{d-L}$$, where d is the distance from the pivot-axis to the middle of the tuning mirror.

This expression is true for small angles $\delta\varphi$ when h_1 and h_2 can be considered linear. In our laser the distance $2L$ between the piezoactuators was 36 mm, and d=40 mm. In our case the necessary calculated ratio of the controlling voltages U_1/U_2 for the tuning mirror to rotate around the pivot-axis is equal to 2.5. Thus, by feeding voltages to the piezoactuators from one power source through a corresponding voltage divider, one can accomplish the prescribed rotation of the tuning mirror.

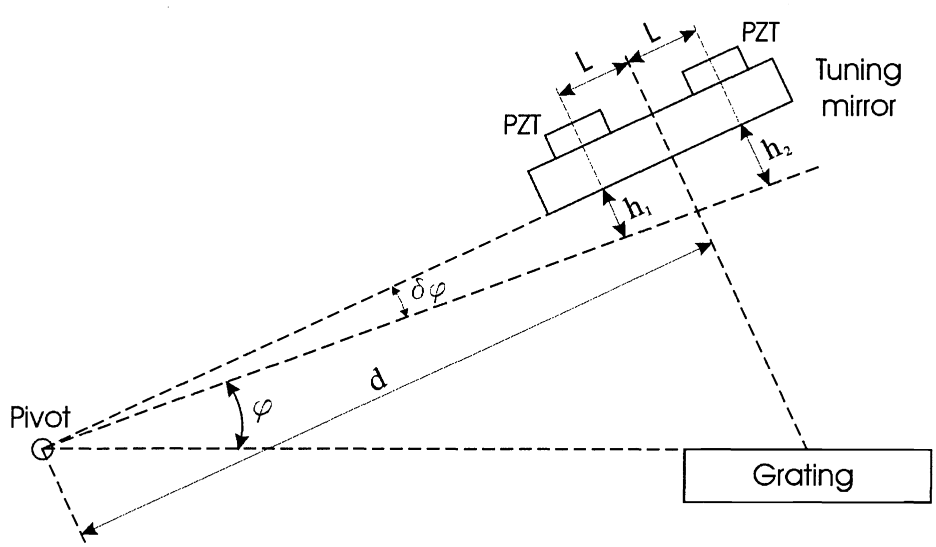

Figure 4. The scheme of controlling the rotation of the tuning mirror in a GIG-oscillator with the aid of two piezotransducers.

The width of the range of the smooth single-frequency scanning in the laser with a GIG-resonator in rotating the tuning mirror with the aid of two PZT is determined by the expression:

$$\Delta\nu = \frac{d \cdot h_2}{d+L} \cdot \frac{c}{\lambda \cdot l_{cav}}$$

For our parameters (d=40 mm, h_2=1.6 µm, L=18 mm, λ = 566 mm, l_{cav}=65 mm) the calculated value of the smooth frequency scanning range $\Delta\nu$ is 9 GHz. The value of h_2 is determined by the sensitivity of the piezoactuators and by the value of the control voltage. As piezoactuators we used nine-layer piezoceramics (15(diameter) x 5 mm size), the control voltage U_2 was equal to ± 200 V. The sensitivity of the piezoceramic transducers came to 4 µm/kV, thus the value of h_2 could not exceed 1.6 µm.

The real range of the laser's smooth single-mode scan was 8 GHz (fig. 5). The ratio of the voltages on the tuning mirror piezoactuators was close to the calculated one (2.5), the procedure of the smooth scanning of the laser's frequency was initially optimized by changing the ration of the voltages on the piezoactuators within a small range. Besides, for a more accurate initial coincidence of the maximum dispersion contour of the grating with the selected oscillation frequency the grating was mounted on an additional piezoelement which could shift in the direction perpendicular to the working surface of the grating. In the process of the smooth scanning of the laser's oscillation frequency this additional piezoelement was not used.

Note that the proposed actuating mechanism based on two piezoelements allows the oscillation frequency to be smoothly scanned in the regime of active frequency stabilization following the scan of the reference interferometer. The error signal of the frequency offsetting is fed to the piezoactuators in the same proportion (1.0:2.5). The scan rate of the laser's oscillation frequency under the conditions of the active frequency stabilization amounted to 1 GHz/sec (8-sec sweep).

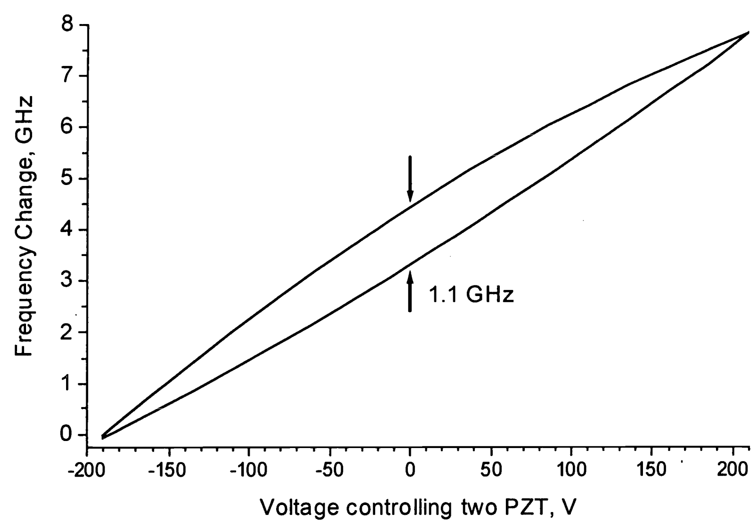

Figure 5. A 8-GHz scan of the SF-DL under two PZT tuning mirror control.

The unquestionable advantages of the advanced method of the smooth scanning of a laser's oscillation frequency are the simplicity of the actuating elements and that of the control procedure as well as the fast operation of the actuating elements – piezoactuators. One should note, however, a marked hysteresis in the dependence of the laser's oscillation frequency on the controlling voltage which is typical of piezoelectric positioners.

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