FREQUENCY-STABILIZED CW DYE LASER WITH PRECISE AUTOMATIC WAVELENGTH TUNING FOR HIGH-RESOLUTION SPECTROSCOPY

B.V. Bondarev, A.V. Karablev, S.M. Kobtsev, and V.M. Lunin

Lenin Komsomol Novosibirsk State University

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A single-frequency cw dye laser with highly stable and linear tuning of the lasing frequency has been developed. The radiation linewidth of the laser does not exceed 10^{-4} cm^{-1}/s. The nonlinearity of lasing frequency scanning in the region 0.5 cm^{-1} is less than 0.1%. The scanning nonlinearity was significantly reduced by monitoring the base line of the reference temperature-stabilized Fabry-Perot interferometer with the help of a capacitive sensor and by using a feedback system to introduce the required correction of the signal controlling the change in the base line of the interferometer. The arrangement of the laser, the electronic control units, and the construction of the reference Fabry-Perot interferometer are described in detail. The laser developed is intended for spectroscopic investigations in a wide range with an absolute accuracy of the order of the linewidth of the laser radiation.

To improve single frequency cw dye lasers (CWSFDLs) having a narrow lasing line (~ 1 MHz) and continuous tuning of the lasing frequency over a wide range (≃ 10–30 MHz) it is necessary to improve the linearity of the tuning of the wavelength of the radiation. The nonlinearity of tuning is determined by the deviation of the dependence of the change in the lasing frequency on the change in the electric signal controlling the tuning from a linear dependence at the threshold of the region of continuous scanning. In the existing CWSFDLs this deviation is at least one to two orders of magnitude greater than the width of the laser line. Thus, for example, in commercial models of CWSFDLs manufactured by Coherent Instruments and Spectra Physics Inc. the nonlinearity of tuning of the lasing frequency in the region of 30 GHz is ~ 2%, (Refs. 1, 2) which with a radiation linewidth of ~ 1 MHz can result in an error in setting the lasing line near the threshold of the region of continuous scanning of several hundreds of megahertz relative to the proposed spectral position. The error in setting the lasing line owing to the nonlinearity of tuning makes it impossible to perform spectroscopic measurements with the help of CWSFDLs with an accuracy of the order of the width of the laser line without additional means for monitoring the change in the lasing frequency, i.e., without so-called "markers". The problem of determining more accurately the spectral position of the lasing line of CWSFDLs can be solved by using superposition wavelength meters,[3] but the most readily available commercial models of such meters[4,5] are unsuitable for this purpose, since the error in the lasing frequency determined with their help is, as a rule, also several hundreds of megahertz.

Linearizing the functional dependence of the laser radiation frequency on the parameter of the controlling signal makes it possible to determine the position of the lasing line with an accuracy of the order of the linewidth in the entire region of continuous scanning, if in at least one arbitrary location in the region of continuous scanning the spectral position of the lasing line is determined to within the linewidth. Absolute calibration of the lasing frequency with this accuracy at an arbitrary location in an arbitrary region of continuous scanning can be performed based on separate lines of a reference spectrum, the frequency of whose lines have been measured with the required accuracy by other methods. We note „hat only one line of a reference spectrum is required tocalibrate the lasing frequency of a laser within each region of continuous scanning, and thereis no need for a "marker" or an ultrahigh-precision wavelength meter.

The purpose of this work was to develop a CWSFDL with highly stable and linear tuning of the lasing frequency for High resolution spectroscopy.

The nonlinearity of tuning in frequency-stabilized CWSFDLs is usually determined by changing the base line of the reference Fabry-Perot interferometer with respect to which the lasing frequency is stabilized. When the base line of the reference interferometer is changed with the help of a piezoelectric ceramic the nonlinearity of scanning in the region "30 MHz can reach 20% and when the base line is changed with the help of an inclined Brewster plate the scanning nonlinearity is equal to 2%. One way to reduce the scanning nonlinearity further is to use a minicomputer to correct the signal controlling the change in the base of the reference interferometer.[5] However this method cannot be implemented in CWSFDLs that are equipped only with analog electronic control units. In the CWSFDL which we developed the nonlinearity of scanning of the lasing frequency is significantly reduced by using a sensor for controlling the change in the base line of the reference interferometer and a feedback system for correcting the signal controlling the change in this base line. The actuating electromechanical element of the system is a piezoelectric ceramic and the controlling element is a capacitive transducer.

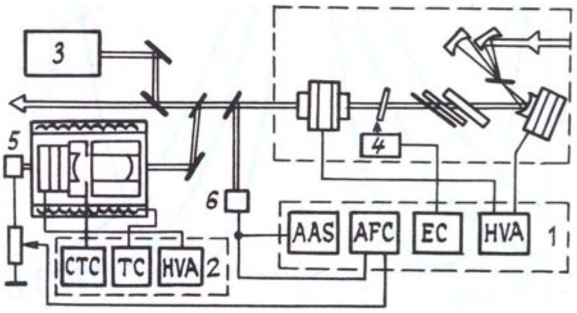

FIG. 1. Block diagram of the CWSFDL developed: 1) laser control unit; 2) reference interferometer control unit; 3) system for visual monitoring of the lasing spectrum; 4) electromechanical drive for displacing the thin etalon; 5, 6) photodetectors.

Figure 1 shows a block diagram of the linear CWSFDL which we developed. The laser employs the basic construction for the radiator and the fluid circulation system.[6,7] The selectors employed in the CWSFDL are as follows: a three component birefringent filter, fabricated following the recommendations of Ref. 8; a quartz Fabry-Perot etalon 0.5 mm thick whose surfaces have a reflectance $R = 0.4$; and, an aluminum absorbing film with a traveling-wave transmittance $T = 0.7$. The optical arrangement of the laser has the following special features. First, the thin etalon is displaced with the help of a special electromechanical drive and, second, a special monoblock is used for simultaneously positioning the absorbing film and the output mirror.

The monoblock consists of two quartz disks, glued together, with the holes at their centers and a PP-4 piezoelectric ceramic in the middle. The output window and the absorbing film are secured to the opposite surfaces of the glued assembly; the distance between them is equal to 2 cm and can be varied by several microns with the help of the piezoelectric ceramic. The monoblock is fabricated so that the out-of-parallelism of its opposite surfaces is equal to only several angular seconds, so that the entire construction is aligned as a single optical element — a selective reflector with an absorbing film. The air gap between the output mirror and the absorbing film is isolated from dust and air flows. The monoblock construction of the selective reflector simplifies the construction and alignment of the CWSFDL and improves the stability of the single-frequency lasing regime. An aluminum film was deposited on a fused quartz substrate; the other side of the substrate was coated with an antireflection coating. The substrate was oriented with the absorbing film turned toward the output mirror. The absorbing film does not have a protective coating; the absence of such a coating did not lead to any degradation of selective reflection during a period of at least one year.

We note that the selective reflector which we used has comparatively high selectivity and makes it possible to achieve single-frequency lasing by increasing the length of the laser cavity up to ~ 1 m. This is important from the viewpoint of using the CWSFDL developed for, for example, intracavity optoacoustic spectroscopy and for other purposes. Figure 2 shows the frequency-selective loss function of thick Fabry-Perot etalons, traditionally employed in CWSFDL, and of a selective reflector with an absorbing film. The characteristics of the selective reflector were calculated by the method described in Ref. 9. One can see that the selective reflector which we used is more selective than the thick Fabry-Perot etalon for a wide range of base lines. From here it also follows that the base line of the selective reflector for a CWSFDL does not have to be chosen from the condition that maximum losses be introduced for the mode that does not compete with the selected mode owing .to the spatially nonuniform saturation of the gain in the thin active medium of the laser, as was done in Ref. 10.

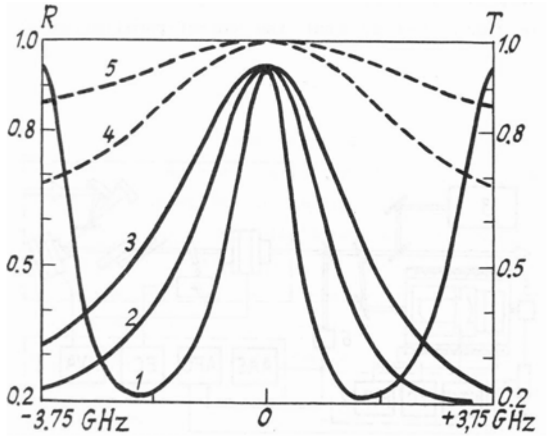

FIG. 2. Frequency-selective loss functions: $T(\nu)$ for Fabry-Perot etalons with a base line of 10 mm, $R_{1,2} = 0.04$ (curve 5) and $R_{1,2} = 0.1$ (4); $R(\nu)$ for a selective reflector with an absorbing film, with a film-mirror distance of 4 (1), 2 (2), and 4/3 cm (3).

The electronic system, which enhances the stability and linearity of tuning of the lasing frequency of the CWSFDL, was constructed in the form of two functionally independent units: the laser control unit and the reference interferometer control unit.

The laser control unit includes the electronic circuits of the following systems: system for automatic adjustment of the selector (AAS) — absorbing film — in the node of the selected mode; automatic frequency control (AFC) system based on the reference Fabry-Perot interferometer; and, a circuit controlling the etalon drive (EC) and high-voltage amplifiers (HVA) for controlling the base line of the selective reflector with the help of the piezoelectric ceramic and the position of the following mirror of the cavity with the help of three piezoelectric ceramics. The AAS system is analogous to the one described in Ref. 11. The base line of the selective reflector is modulated with a frequency of 5 kHz. In this laser the AAS system is supplemented with a circuit for automatically regulating the gain in order to improve the operating regime of the synchronous detector in the entire range of output powers of the laser. The operation of the AFC system is based on the principle of stabilization of the laser frequency according to the slope of the transmission peak of the reference Fabry-Perot interferometer. An important element of the AFC system is the circuit normalizing the error signal the output power of the dye laser; this makes it possible to maintain a constant gain and a constant transmission band of the AFC system in the entire region of lasing of the dye.

With the help of collimating mirror with a piezoelectric package consisting of three P-3 piezoelectric ceramics it is possible to scan the radiation frequency of the CWSFDL continuously in a 15 GHz range with a total amplitude of the voltage across the piezoelectric package equal to 500 V. Continuous scanning of the frequency in a spectral region whose width exceeds that of the region of dispersion of the selective reflector 17.5 GHz) is possible only if the transmission peak of the thin etalon is scanned synchronously. To achieve such scanning we developed an electromechanical drive for the thin etalon and a circuit for controlling the drive. The electromechanical drive was designed based on a DPR-52 motor and it makes it possible to turn the thin etalon continuously by ±2.5° with a frequency of up to 100 Hz. A special coupling circuit is employed for linear scanning of the transmission peak of the etalon relative to the voltage controlling the rotation of the etalon. This circuit takes the square root of the controlling voltage and controls the drive with the help of the signal obtained in this manner. Synchronous scanning of the lasing frequency and the transmission peak of the thin etalon is achieved by applying a certain fraction of the voltage controlling the scanning to the piezoelectric package of the collimating mirror and the circuit controlling the etalon drive. The circuit controlling the etalon drive and the drive itself were tested separately in a self-scanning narrow-band cw dye laser[12] in a regime when the wavelength of the radiation is set by the position of the thin etalon. No additional fluctuations or drift of the wavelength of the radiation attributable to the use of the etalon drive were observed. The nonlinearity of wavelength scanning performed with the help of the thin etalon did not exceed 1.5% over a range of 180 GHz.

The unit controlling the reference interferometer contains electronic circuits controlling the capacitive transducer (CTC), the thermostat (TC), and the high-voltage amplifier (HVA). A scanned confocal interferometer with a dispersion range of 1.5 GHz and a sharpness factor of three was employed as the reference interferometer. The temperature of the interferometer is maintained constant to within 0.005°C. The construction of the reference interferometer is shown in Fig. 3. The external thermally insulating casing is made of solid foam insulation. A heater with a temperature-sensitive element, which is necessary for active stabilization of the interferometer temperature, is placed inside this casing. One mirror of the interferometer is rigidly connected with a fused quartz cylinder, which is placed between the interferometer mirrors and is several millimeters shorter than the base line of the interferometer.

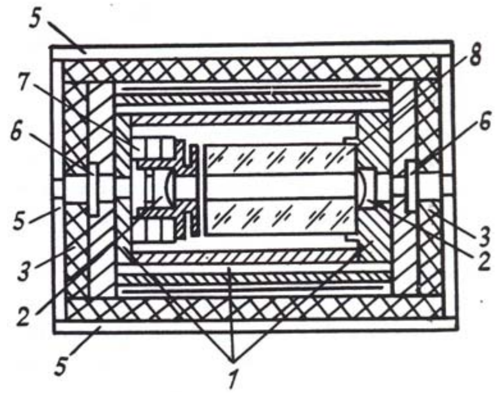

FIG. 3. The construction of the reference interferometer: 1) interior invar casing of the interferometer; 2) interferometer mirror; 3) solid foam insulation; 4) heater filament winding; 5) interferometer body; 6) quartz window coated with an antireflective coating; 7) PP-4 piezoelectric ceramic; 8) quartz cylinder.

A capacitive transducer for controlling the change in the interferometer base line is placed in this specially provided gap. One plate of the transducer consists of a chemically deposited silver coating on the end face of the quartz cylinder. The opposite plate consists of a metal disk connected with the other mirror of the interferometer, which can be moved along the axis of the interferometer with the help of three PP-4 piezoelectric ceramics. The distance between the plates of the capacitive transducer is equal to 200 μm. The capacitive transducer is part of an LS oscillator, which is placed in the invar casing of the interferometer and whose inductance consists of a silver coating chemically deposited in a spiral on the lateral surface of the quartz cylinder. A change in the base line of the interferometer results in a change of the frequency of this LS oscillator (the average frequency ≅ 30 MHz) and is recorded by a special circuit in the interferometer control unit. The circuit converts the change in the frequency of the LS oscillator into a digital code, which is converted into an analog voltage with the help of a 12-bit DAC. The signal obtained in this manner is fed into a difference circuit, which compares the level of this signal with the level of this signal controlling the scanning of the base line of the interferometer. The difference of the levels of these signals is fed in antiphase into one of the inputs of the HVA control unit, which controls the piezoelectric ceramics of the interferometer. Thus any deviations of the scanning from linearity are compensated by negative feedback.

The lasing spectrum of the CWSFDL was monitored with the help of two scanning Fabry-Perot interferometers with the dispersion ranges of 15 GHz and 250 MHz and sharpness factors of at least 50. The entire system which we used for monitoring visually the lasing spectrum of narrow-band cw lasers is described in detail in Ref. 13. The output power of the CWSFDL was monitored with an LM-2 power meter. An ILA-120-1 argon laser was used as the pump laser.

The characteristics of the single-frequency cw dye (rhodamine 6G) laser which we developed are as follows:

the maximum output power exceeds 50 mW with pumping by all lines of the linearly polarized radiation of a 3 W argon laser;

the linewidth of the radiation over a period of 1 sec does not exceeds 3 MHz;

the rate of drift of the lasing frequency does not exceed 60 MHz/h;

the lasing frequency can be tuned continuously over a range of 15 GHz;

the nonlinearity of tuning of the lasing frequency does not exceed 0.1%.

The CWSFDL which we developed based on three rhodamine dyes made in this country — unsubstituted, 6G and 4S perchlorate — has a tuning range of about 550–650 nm.[14] This laser makes it possible to expand significantly the possibilities of many research methods used in high-resolution spectroscopy as well as to perform precise spectroscopic studies with an absolute accuracy of the order of the linewidth of the laser radiation. An accuracy of 10^{-8}–10^{-9} is sufficient for many spectroscopic measurements.

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