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Frequency-stabilised external-cavity semiconductor laser

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***Abstract*. The design and characteristics of a semiconductor laser with the modified external Littrow resonator are described. The additional output mirror of the V-shaped resonator made the system more efficient and convenient. The laser radiation frequency is stabilised with the help of magnetooptical Faraday and circular dichroism effects in rubidium vapour.**

Keywords: *semiconductor lasers, resonators, frequency stabilisation.*

1. Introduction

Semiconductor lasers are very efficient devices which permit the solution of many problems of laser physics and technology in a simpler and more reliable way, often at a much lower cost. For example, well-known advances in atomic physics in the two last decades have been achieved to a great extent due to the development of semiconductor lasers. In this connection, external-cavity semiconductor lasers emitting high-power monochromatic radiation at frequencies of many important atomic resonances are of great interest. At present several types of external-cavity semiconductor lasers are developed for solving a variety of problems (see, for example, [1 – 6]). Nevertheless, a great demand of research and educational laboratories for reliable and easily available coherent radiation sources makes important a further development of such lasers.

At present the most popular are two basic schemes of the external cavity for semiconductor lasers – the Littrow and Littman resonators shown in Fig. 1. In the Littrow resonator, feedback is performed through nonzero-order diffraction from a grating, while radiation is coupled out of the resonator in the zero-order diffraction. Although such a resonator scheme is very simple and is quite popular, it has some disadvantages. It cannot be used at very large diffraction angles required for increasing the resonator dispersion. In addition, the external coupling coefficient of the resonator is completely determined by the grating parameters and cannot be optimised in each particular case.

The Littman resonator allows the operation at larger diffraction angles, and the fraction of radiation coupled out of the resonator can be easily controlled by adjusting the transmission of the output mirror. However, radiation in the Littman scheme interacts twice with the gating during round trip in the resonator. In this case, the grating reflectivity for grazing diffraction is considerably suppressed due to vignetting of grating grooves, which reduces the Q-factor of the resonator [7].

In this paper, we describe the design of an external-cavity semiconductor laser representing a simple and convenient modification of the standard Littrow resonator. Wavelengths were selected with a profiled diffraction grating. Radiation was coupled out of the resonator with the help of an additional semitransparent mirror, which allowed a convenient variation of the external coupling coefficient of the resonator. We also stabilised the laser frequency with the help of magnetooptical Faraday and circular dichroism effects in rubidium vapour. The laser described in the paper was developed to trap and cool rubidium atoms in a magnetooptical trap.

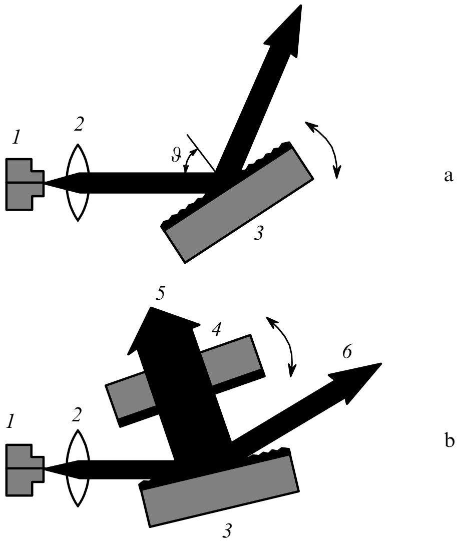

Figure 1. External cavities of semiconductor lasers based on the Littrow (a) and Littman (b) schemes: (*1*) semiconductor laser; (*2*) collimator; (*3*) diffraction grating; (*4*) mirror; (*5*) main beam; (*6*) additional beam.

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2. Laser design

An important parameter of a laser is the fraction of radiation coupled out of the laser resonator (the external coupling coefficient of the resonator). The optimal value of this parameter is a complicated function of the gain in the active medium, field saturation, and resonator losses. In practice, it is preferable to have the opportunity to vary the external coupling coefficient of the resonator, by selecting its optimal value experimentally. The external coupling coefficient for the most popular Littrow resonator (Fig. 1a) is completely determined by the grating parameters and cannot be arbitrarily varied. This problem can be solved by using the V-type resonator, from which radiation is coupled out through an additional semitransparent mirror (Fig. 2) [8]. Note that the resonator of this type was earlier used to select wavelengths in an erbium-doped fibre laser [9].

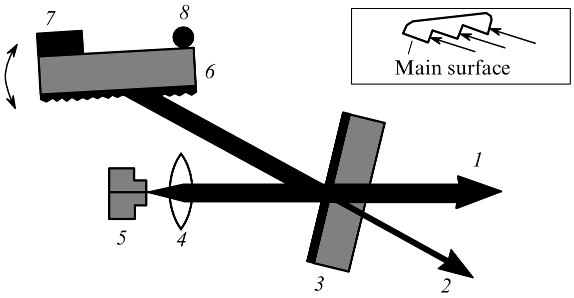

Figure 2. V-type external cavity of a semiconductor laser: (*1*) main beam; (*2*) additional beam; (*3*) output mirror; (*4*) collimator ($f = 5$ mm); (*5*) laser diode; (*6*) diffraction grating; (*7*) piezoelectric ceramic element; (*8*) rotation axis of the diffraction grating.

We used in the study a 600-lines mm^{-1} diffraction grating with the blazing angle $\sim 30°$. This blazing angle is determined by the orientation of the main surface of a triangle groove of the grating (see inset in Fig. 2). Such a surface of the groove allows operation at the diffraction angles $\theta \simeq 30°$. The manufacturing technology of diffraction gratings provides an approximately triangle profile of the grating groove, allowing the use of another face of the groove (the so-called inoperative face of the groove). This allows one to use larger diffraction angles, thereby increasing considerably the angular dispersion of the resonator [7].

By using inoperative faces of the groove, we could work at the diffraction angle $\theta = 70°$ corresponding to the fourth diffraction order for a wavelength of 780 nm. The reflection coefficient for the fourth-order diffraction was $\sim 60\,\%$. The reflection coefficient for the zero-order diffraction for $\theta = 70°$ proved to be very small ($\sim 1\,\%$). As a result, a laser with the traditional Littrow resonator and the diffraction grating available had rather poor characteristics. It is this circumstance that forced us to modify the traditional Littrow resonator. Note here that the use of inoperative faces of grating grooves to increase the grating dispersion is described in monograph [10] devoted to classical spectral instruments.

We used standard ML6XX24 laser diodes (Mitsubishi) without antireflection coatings. In this case, as is well known [1], the laser resonator consists of two parts: a crystal resonator itself and an external resonator. Continuous tuning of the laser can be performed only upon simultaneous tuning of both resonators, which is necessary to suppress the radiation frequency pulling effect. In our laser, this was achieved by using the simultaneous modulation of the laser diode current and the tilt of the diffraction grating by a piezoelectric ceramic element.

The external resonator of the laser had a length of 3.5 cm. As a collimator, a lens with a focal distance of 5 mm was used, which had antireflection coatings on both sides. The collimator position was adjusted so that the output beam of the laser diode retained its transverse size upon visual observation at a distance of 2 – 3 m. After the alignment, the collimator was glued with a stomatology plastic to the resonator base.

To obtain a stable operation of a laser diode, its temperature should be carefully stabilised. We used the following stabilisation scheme. The laser diode was mounted in a copper housing. Temperature was measured with a 10-kΩ thermal resistance placed in one of the arms of a Witstone bridge. The output signal of the bridge was amplified in an AD622AN amplifier and was used to control the power supply of a Peltier element stabilising the laser diode temperature. The temperature stability of the external resonator was better than 1 mK. The temperature stabilisation of the external resonator was passive and was performed due to a good thermal contact between the resonator and a massive metal optical table top.

3. Laser parameters

We used a laser diode emitting at a wavelength of 785 nm at 25 °C, so that it was necessary to cool it down to 14 °C in experiments with rubidium vapour to obtain lasing at $\sim$ 781 nm. In this case, the output power was 35 mW for the pump current 72 mA. The laser with the V-resonator emits two beams (Fig. 2). (We did not use a very weak beam emerging from the laser in the zero diffraction order.) The direction of the main beam is independent of the orientation of the grating and mirror and is only determined by the position of the diode and collimator. The direction of the second beam changes during tuning, as in the case of a laser with the Littrow resonator. When a plane semitransparent mirror was used with the transmission $T = 45\,\%$, the output power of the laser was 18 mW (14 mW in the main and 4mW in the second beam). For a mirror with $T \simeq 60\,\%$, the laser emitted 21 and 3 mW in these beams, respectively. The tuning range of the laser also depended on the transmission of the output mirror (see below). Thus, as expected, the external coupling coefficient of the semiconductor laser resonator substantially affects its parameters. For the V-type resonator, the variation of the external coupling coefficient proves to be quite simple.

The laser parameters were measured using the setup shown in Fig. 3. The laser wavelength was measured with a grating spectrograph with a linear dispersion of 0.36 nm cm^{-1} on a TV monitor and, more accurately, by using a precision λ-meter with the 50-MHz resolution. A coarse tuning of the laser was performed by rotating the output mirror mounted on an alignment head. With a mirror having the transmission coefficient $T = 45\,\%$, the laser wavelength could be tuned from 775 to 785 nm at a constant temperature of the laser diode equal to 14 °C. The width of the tuning range decreased when a mirror with a higher transmission coefficient was used.

A continuous tuning of the laser was controlled with the help of the linear absorption spectra of rubidium vapour. A weak laser beam passed through a 7.5-cm cell at room temperature. The cell contained rubidium vapour of the natural isotopic composition without a buffer gas. During these measurements, an intense counterpropagating laser bean was blocked (Fig. 3). The linear transmission spectrum is shown in Fig. 4a. This spectrum was obtained by averaging over 16 recordings for ~1 s. One can see that the width of the continuous tuning range exceeds 9 GHz. A weak decrease in the radiation intensity observed in Fig. 4a is caused by the laser current modulation.

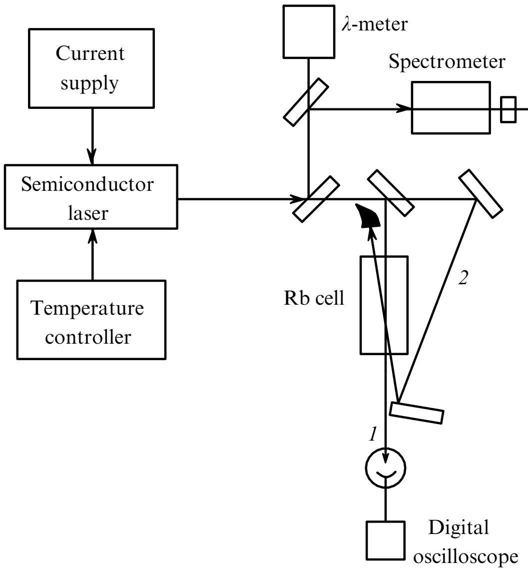

Figure 3. Scheme for measuring spectral characteristics of laser radiation. A weak and strong beams in the scheme for measuring saturated absorption spectra are indicated by (*1*) and (*2*), respectively.

It is useful to compare the measured linear absorption spectrum with the calculated spectrum. The spectrum was calculated by using the hyperfine-splitting parameters of the ^{87}Rb and ^{85}Rb isotopes measured in [11] and the lifetime of the $^2P_{3/2}$ level of the Rb atom equal to 25 ns [12]. Figure 5 shows the energy level diagram of the ^{87}Rb isotope. The calculated linear absorption spectrum is presented in Fig. 4b. This spectrum coincides with the experimental spectrum within 5 % if the saturated vapour pressure of Rb reported in [13] is used. The saturated vapour pressure reported in [14] proves to be lower by 20 % than the measured pressure.

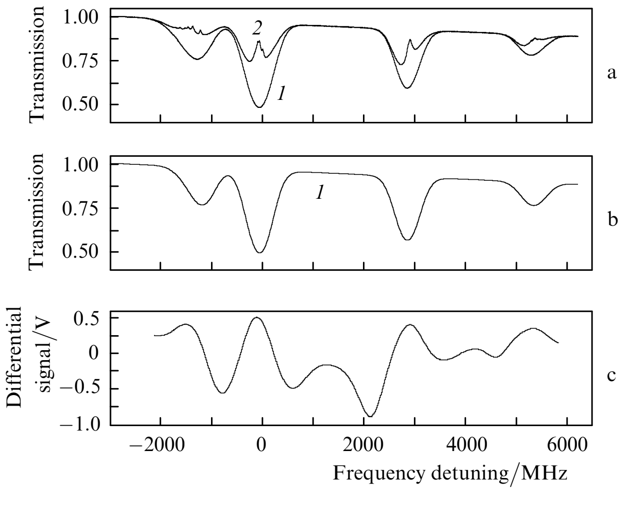

Figure 4. Experimental (a) and calculated (b) transmission spectra of the D_2 line of rubidium: linear transmission spectrum (*1*) and saturated absorption resonances in counterpropagating waves (*2*) and the differential signal of the frequency stabilisation system (c).

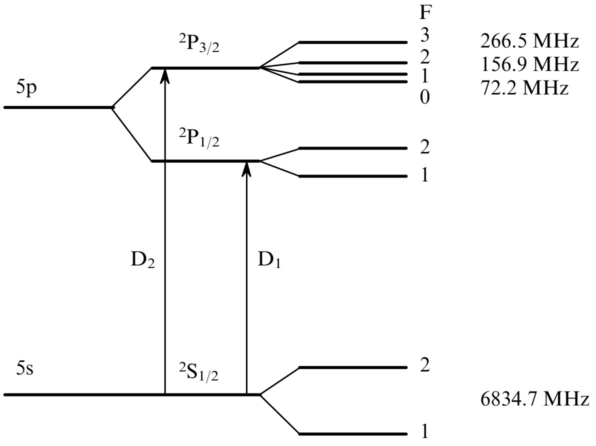

Figure 5. Energy level diagram of the fine and hyperfine states of the ^{87}Rb isotope. Frequencies indicate hyperfine splittings [11].

The passive stability of the laser radiation frequency was measured by two methods. In the first method, a change in the radiation absorption by rubidium vapour was recorded. These measurements gave the frequency drift ~12 MHz min^{-1} for approximately 20 min. In the second method, the λ-meter was used to obtain a close value of the frequency drift of 15 MHz min^{-1} for observation during the same time.

The width of the laser line is its important parameter. It can be most reliably measured from beats for two independent lasers. We estimated the linewidth by measuring the widths of saturated absorption resonances for counterpropagating waves in rubidium vapour. The saturated absorption spectrum is shown in Fig. 4a (and in an expanded scale, in Fig. 6). These spectra were obtained by averaging over 16 recordings for ~1 s. Consider the example of the resonance on the hyperfine $F_g = 2 \longrightarrow F_e = 3$ transition. The half width at half-maximum of this resonance is determined by a few components [15]: the radiative linewidth of the transition (3 MHz in our case [12]), the width of the Bennett peak in the velocity distribution of atoms at the upper level, the broadening of the resonance due to noncollinearity of a strong and weak beams [16], and the laser linewidth. Thus, the minimal possible linewidth of the resonance is 6 MHz in our case. The width of the Bennett peak contains the contribution of power broadening. To elucidate the role of the power broadening of resonances recorded in our experiments, we measured their widths for different powers of the strong beam (Fig.7). By extrapolating these data to the zero beam power, we obtained the width of the resonance equal to ~7 MHz.

Another component of the nonlinear resonance width is caused by the noncollinearity of laser beams and can be

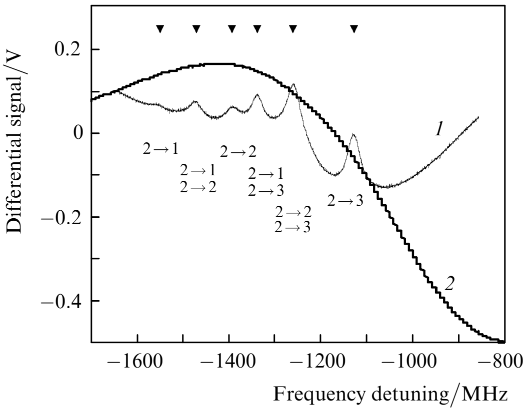

Figure 6. Saturated absorption resonances (*1*) and a signal of the frequency stabilisation system (*2*) in the vicinity of the $F_g = 2 \rightarrow F_e$ hyperfine transitions in the ^{87}Rb isotope. The triangles indicate the calculated positions of resonances [11]. The hyperfine states responsible for the appearance of resonances are shown.

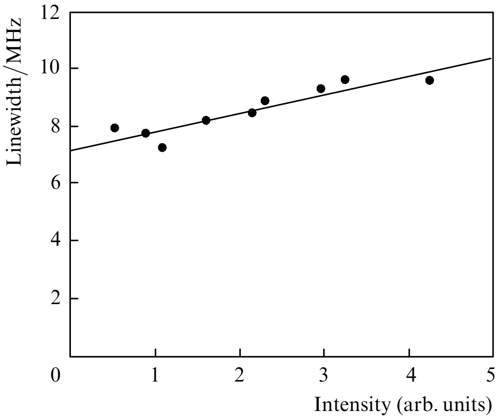

Figure 7. Power dependence of the saturated absorption resonance width in counterpropagating waves for the $F_g = 2 \rightarrow F_e = 3$ hyperfine transition in rubidium.

estimated only roughly. Our optical system did not have Faraday isolators, and therefore, the noncollinearity of weak and strong laser beams could not be less than $\sim 3 \times 10^{-3}$ rad. This angle contributes to the width at the 1-MHz level [16]. These rough estimates allow us to conclude that the laser linewidth is less than 1 MHz.

At present many methods are developed for active stabilisation of the laser frequency. The application of one or another method is determined by the specific conditions of the problem. Our laser was developed for cooling rubidium vapour in a magnetooptical trap. In this case, it is desirable to use the stabilisation method that does not employ modulation of the laser radiation frequency and allows frequency stabilisation at any frequency near the atomic resonance. The frequency stabilisation method based on magnetooptical Faraday and circular dichroism effects in rubidium vapour [method for frequency stabilisation of semiconductor lasers called dichroic atomic vapour laser lock (DAVLL) (4, 5)] satisfies these requirements. This method was first applied to LNA lasers [17]. It does not employ laser frequency modulation and allows one to stabilise the radiation frequency virtually at any frequency within the linear absorption band. The operation of the stabilisation system is explained in Fig. 8a. Linearly polarised radiation is directed to a cell with Rb vapour in a longitudinal magnetic field. Two circularly polarised components of this radiation acquire the relative phase shift in the cell due to the Faraday effect and are differently absorbed because of circular dichroism. The elliptically polarised radiation behind the cell is decomposed by a $\lambda/4$ phase plate into two mutually orthogonal linearly polarised components, which then are separated by a Glan prism and are directed to two photodiodes. The difference signal from these photodiodes is used to stabilise the laser frequency. Depending on the orientation of the optical axis of the $\lambda/4$ phase plate and Glan prism, the value of the difference signal can be determined either only by the Faraday effect or only by circular dichroism or by their combination [5]. The orientation of these optical elements, the magnetic field strength, and cell temperature were selected in the experiment so that the frequency dependence of the difference signal at the required spectral region would be maximal. For example, it achieved ~ 2 mV MHz^{-1} near the centre of the $F_g = 2 \rightarrow F_e$ hyperfine transition in the ^{87}Rb isotope.

The magnetic field optimal for stabilisation depends on many factors in a complicated way and should be adjusted experimentally. In our setup, a variable magnetic field was produced with the help of a permanent samarium-cobalt magnet, a magnetic circuit, and a movable jumper for removing a part of the magnetic flux. The magnet design is shown in Fig. 8b. This system provided the variation of the magnetic field strength in the cell with Rb vapour from 130 to 360 G. The optimal field strength was 200 G. The cell with Rb vapour had a diameter of 2 cm and its temperature was maintained at 40 °C.

This stabilisation scheme proved to be quite efficient. It provided a reliable stabilisation of the laser frequency in the frequency range ±200 MHz in the vicinity of the

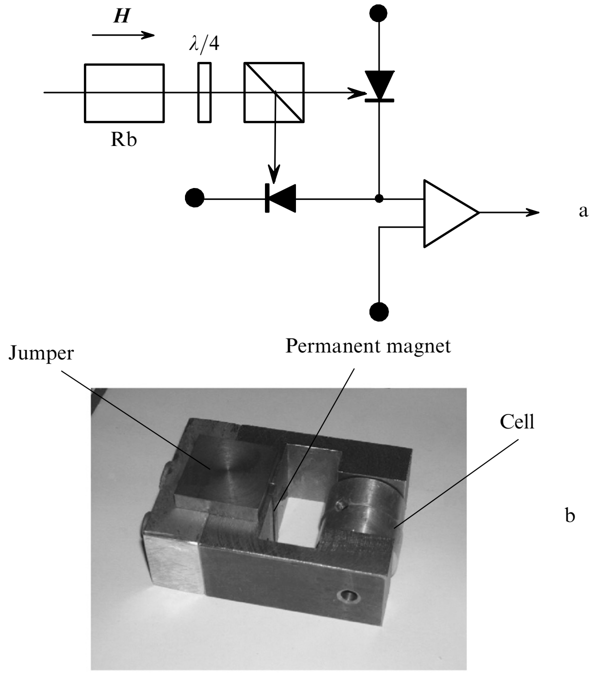

Figure 8. Laser frequency stabilisation scheme (a). Photograph shows the magnet design (b).

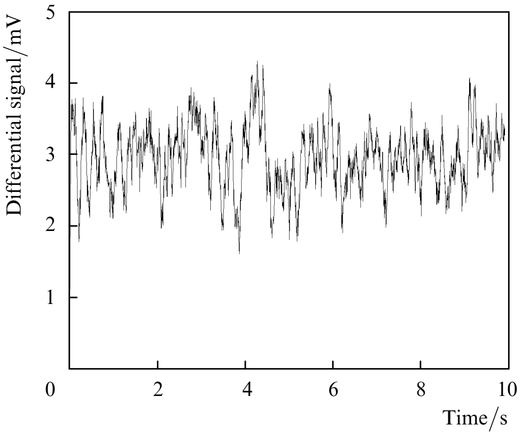

Figure 9. Noise track of the differential signal of the frequency-stabilised laser; the system sensitivity is 2 mV MHz^{-1}, the averaging time is 80 ms.

$F_g = 2 \rightarrow F_e = 3$ transition of the ^{87}Rb isotope and had the frequency lock range $\sim$600 MHz. Figure 6 shows signals that are important for the system operation: the saturation absorption spectrum for counterpropagating waves at the $F_g = 2 \rightarrow F_e$ transition in the ^{87}Rb isotope and the difference signal used to stabilise the laser frequency. The noise track of the differential signal recorded by averaging for 80 ms is shown in Fig. 9.

4. Conclusions

We have presented the parameters of a simple external-cavity semiconductor laser based on a standard laser diode without antireflection coatings. The wavelength selection was performed with a profiled diffraction grating in the resonator representing a simple modification of the Littrow resonator. The resonator has the V shape with an additional semitransparent output coupler mirror. This mirror allows one to adjust easily the external coupling coefficient of the resonator to achieve the optimal tuning range or the optimal output power of the laser. The output power of this laser was $\sim$50 % of that of a laser diode without the external resonator. The continuous tuning range was no less than 9 GHz and the linewidth $\sim$1 MHz. The laser frequency was stabilised with the help of a stabilisation system based on the Faraday and circular dichroism effects in rubidium vapour. A simple and reliable design of a permanent magnet for the use in the system is proposed.

The V-resonator of diode lasers offers some other advantages compared to the conventional Littrow scheme. The selection of the optimal diffraction grating in this resonator is quite simple because it should now have the maximum possible reflectivity. Another advantage is that the direction of the main laser beam does not change upon laser tuning and any manipulations with the output mirror and diffraction grating, which simplifies the alignment of the rest of the optical scheme. In addition, the resonator can be made rather compact.

Note in conclusion that the laser operation has been recently conclusively demonstrated. Two lasers of this design have been used to build a reliable magnetooptical trap for rubidium atoms [18].

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