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Spectral control of powerful diode lasers with enhanced output by external cavity based on volume holographic grating

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Abstract. To achieve the maximum efficiency in single-frequency lasing mode of laser diode with external cavity, it is necessary to minimize losses in the optical system for the output beam and to provide the optimal frequency-selective feedback. In this paper, we have investigated the scheme of an external cavity diode laser (ECDL) based on phase volume holographic grating (VHG). Angular and spectral selectivities of the holographic grating allow to adjust the optical feedback with low losses in the cavity, and it can be used for the frequency narrowing of diode-array bars. Here, the optimal parameters of VHG and the temperature dependence of the diode laser bar spectrum have been studied, and the proposals on VHG design have been developed.

Keywords: diode laser, spectrum, temperature, external cavity, volume holographic grating.

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1. Introduction

To control of laser diodes radiation spectrum is important for many laser applications, namely: laser spectroscopy, laser cooling of atoms, control of quantum states of atoms and molecules, atomic interferometry, optical pumping of powerful solid-state lasers.

It is known that, in the general case, the spectrum of radiation of a semiconductor laser is determined by the spectral dependence of the amplification of the active medium and frequency selectivity of a laser cavity, formed by the faces of a laser crystal or an external cavity. The gain spectrum of laser is determined by elemental composition of laser and the peculiarities of the junction structure of the semiconductor laser. The peak position of laser gain depends on the temperature of the crystal and the excitation current, and can be shifted in more or less wide limits by their regulation. To obtain the radiation with a narrow spectrum, the most common method is to create a selective feedback in a laser using an external cavity containing dispersion elements, in particular, diffraction gratings [1].

An important parameter of the frequency selection scheme that ultimately determines the characteristics of the laser is the optical feedback level that should be sufficient to suppress undesirable frequencies and at the same time would not excessive in terms of the effect on the energy parameters of the laser. In this relation, we would like to draw attention to the possibility of creating an adjustable feedback in the external cavity with volume holographic grating (VGH). In recent years, the external cavity with VGH have attracted considerable attention both for creation of high-monochromatic lasers with high stability of the radiation wavelength [2-4], and, importantly, for work in external cavities of laser-array bars with high output power of radiation [5, 6].

In this paper, the general principles of the semiconductor lasers radiation spectrum control are illustrated using the examples of schemes with an external resonator including VHG, which makes it possible to achieve an increased efficiency and output power in comparison with traditional cavities with reflective gratings. The precise feedback control in this design of external cavities is achieved by fine tuning the VHG position. The results of an experimental study of the dependence of the spectrum and the output power of a laser-array bar on temperature are also given in order to study the additional control parameters of laser diodes and diode arrays with external cavities.

2. Temperature dependence of the laser diode bar radiation spectra

To develop the laser systems with controlled output spectrum, the temperature dependence of the laser radiation wavelength should be taken into account. It is known that the amplification line of a semiconductor laser shifts to higher energies with increasing the injecting current, and the temperature shift is opposite. For example, for the InGaAlP laser diode the gain curve

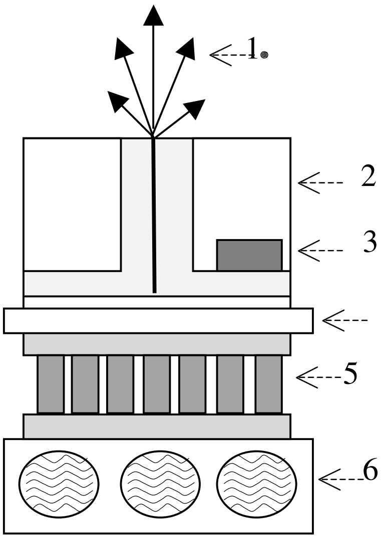

Fig. 1. The laser diode bar with the temperature control units: laser output (1), laser diode (2), temperature sensor (3), brass plate (4), Peltier elements (5), and aluminum heat sinks with cooling water (6).

undergoes a temperature shift with a coefficient of about 0.23 nm/K. The cavity modes shift due to the laser crystal thermal expansion and due to the refractive index changes with the temperature and current. For the single longitudinal mode, the coefficients of temperature and current dependence on average are +0.06 nm/K (–45 GHz/K) and + 0.003 nm/mA (–2.4 GHz/K) [7]. The difference in the temperature dependence of the gain curve and the resonance modes leads to jumping modes at the temperature changes and, hence, to limiting the achievable region of continuous frequency tuning. In addition to external factors, the aging of the laser diode has significant influence on the wavelength of output radiation.

We performed more detailed investigations of the temperature shift of the line of generation of the diode-array bar to ascertain the influence of temperature on the output parameters of the laser and the required level of temperature stability in wavelength-sensitive applications of this type lasers, in particular, in spectroscopy and optical pumping of solid-state lasers.

The laser diode bar (20 W, 25 A, "Silver Bullet" type, Northrop Grumman) output power and spectrum within the temperature range 10…46 °C was studied. The bar of six laser diodes were soldered to thin (2 mm) brass silver plated plates with three Peltier elements fastened through the thermal paste to the opposite sides of the brass plates (Fig. 1). Opposite side of Peltier elements was fixed to common water cooled aluminum heat sink radiator. The rectangular 500 μs current pulses with the amplitude close to 13 A were used for laser diodes operation. The radiation spectrum was recorded by the Ocean Optics USB 2000 spectrometer. The temperature of laser diodes was measured by the miniature temperature sensor Honeywell 777.

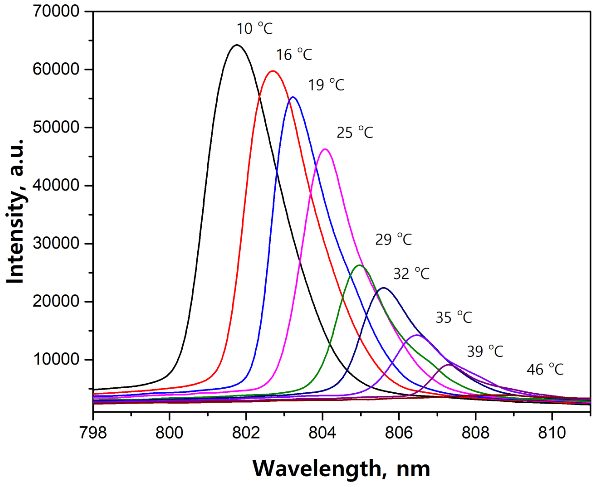

Fig. 2. Dependence of the laser diode radiation spectrum on temperature.

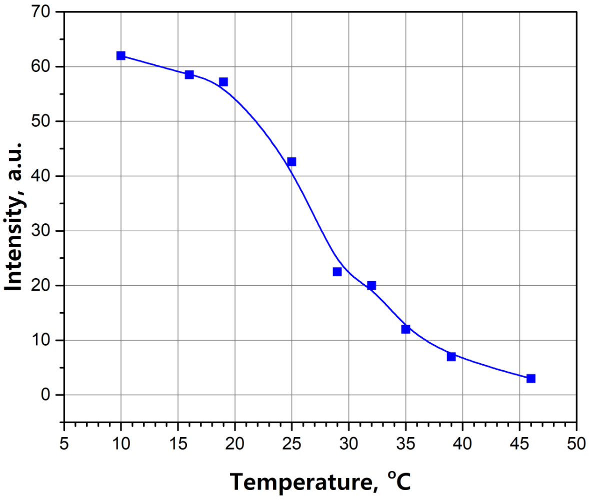

Fig. 3. Diode laser output (a.u.) vs temperature (°C).

Laser emission spectral lines shapes of single laser diode from the diode bar on the temperature within the range 10 to 46 °C is shown in Fig. 2. The power dropping with temperature is shown in Fig. 3 and gain peak shift – in Fig. 4.

The gain peaks spectral positions of separate laser diodes from single bar was varied in the spectral range not wider than 1 nm, and the temperature dependence of intensity and spectrum for all six investigated diodes were similar. The gain peak temperature shift is 0.34 nm/K in the studied temperature range. The shapes of emission spectral lines for all temperatures in the studied range are practically identical with spectrometer resolution limited FWHM near 3-4 nm. The temperature shifts of gain peaks and lowering the laser output are typical for semiconductor laser diodes, and the results are in good agreement with the known theoretical models [8].

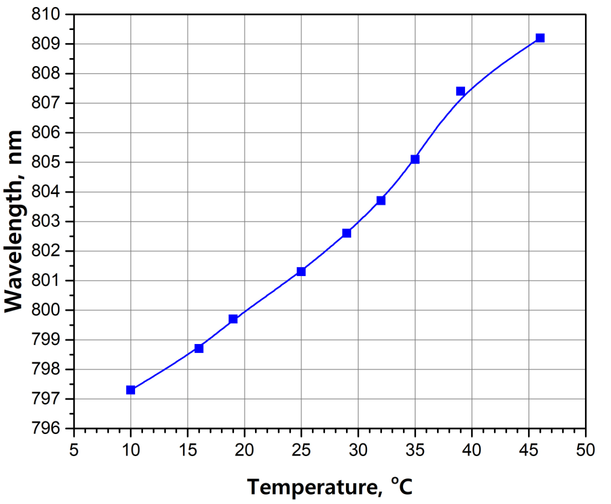

Fig. 4. Gain peaks positions (nm) vs temperature (°C).

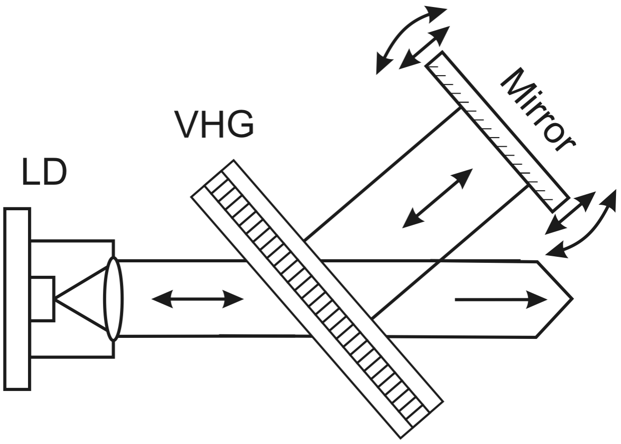

Fig. 5. Schematic of the external cavity diode laser based on the transmitting volume holographic grating.

3. VHG for tunable external-cavity diode lasers

Most of tunable external-cavity diode lasers are based on one of two main configurations: Littrow or Littman–Metcalf setup [1]. The output beam of the laser diode is collimated using a lens and directed on a diffraction grating. The optical feedback level in external cavity diode lasers is defined by the portion of laser output directed into the laser active volume by external cavity elements (grating or grating + mirror). The regulation of optical feedback level within wide limits is rather complicated: the diffraction efficiency of metallic blazed or surface holographic grating is fixed and the mirror misalignment is only applied for regulation of the reflected beam intensity.

We analyzed the optical feedback control in Littman–Metcalf configuration of external cavity diode laser with VHG (Fig. 5).

The diffraction efficiency of volume holographic grating is angle- and wavelength-dependent and reaches its maximum under the Bragg conditions.

The optimal optical feedback is rather important for stable laser operation and for maximizing the laser output. For a laser diode, the low quality of its resonator formed by parallel faces of a laser crystal makes the mode of generation extremely sensitive to optical feedback. This sensitivity is further enhanced by the weak spectral dependence of the amplification curve of the active medium. The real influence of the feedback on the radiation parameters (spectrum, modular composition, output power) depends on the phase, amplitude and polarization of the light coming back into the laser [9, 10]. For different levels of optical feedback, modes with expanding or narrowing the line of radiation, mode jumps, coherence collapse with chaotic regime of non-damped relaxation oscillations and, finally, stable single-mode generation in the mode of strong optical feedback with substantially reduced line width and stable laser operation take place. In the case of sufficient frequency selectivity of the resonator, the laser operates in a single longitudinal mode with a narrow line for all phases of radiation that are returned to the laser cavity.

VHG is the diffractive optical element, which operation is described by the Kogelnik theory [11]. The angular selectivity of the transmission VHG with a sinusoidal profile of the refractive index spatial modulation is determined by the Kogelnik formula:

$$\eta = \frac{\sin^2\left(\xi^2 + \nu^2\right)^{1/2}}{1 + \dfrac{\xi^2}{\nu^2}}$$

where $\nu = \dfrac{\pi T n_1}{\lambda \cos\left(\theta_0 + \Delta\theta\right)}$ is the phase incursion, the parameter that defines the maximum diffraction efficiency of VHG, when the Bragg condition is satisfied (n_1 – modulation of refraction index of photopolymer with a thickness T; θ_0 – Bragg angle in medium; $\Delta\theta$ – detuning from Bragg angle in the medium; λ – laser emission wavelength); $\xi = \dfrac{\pi T \Delta\theta \cos\theta_0}{\lambda \cos\left(\theta_0 + \Delta\theta\right)} - \dfrac{\pi T \Delta\lambda}{2 n \Lambda^2 \cos\left(\theta_0 + \Delta\theta\right)}$ are angular and wavelength deviations from the Bragg condition (Λ is the spatial period of modulation of refractive index of photopolymer grating; $\Delta\lambda$ – deviation from the central wavelength of laser emission; n – average refraction index of grating media (photopolymer)). If $\nu = \dfrac{\pi}{2}$ and $\Delta\theta = 0$, then the efficiency of transmitting grating is 100%.

Rotating VHG makes it possible to adjust the energy distribution of the laser radiation between the external resonator and the output beam (Fig. 6).

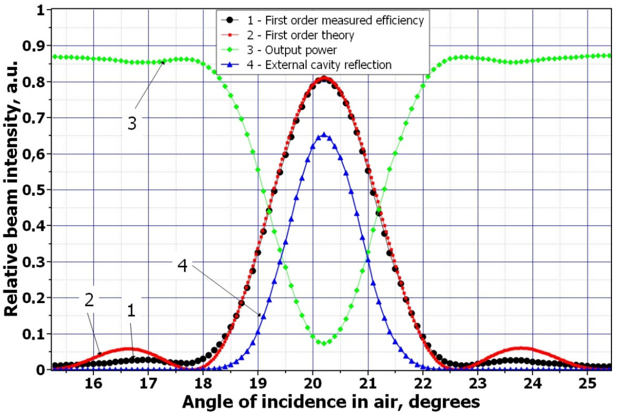

Fig. 6. Angular dependence of the partial beams intensity in the extended cavity.

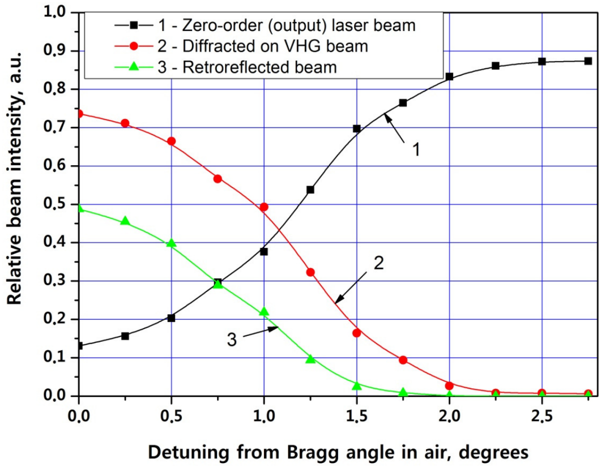

Fig. 7. Optical intensity redistribution at the VHG presence in the laser cavity.

In the external cavity design shown Fig. 5, rotation of the mirror allows tuning the coarse wavelength, and the mirror shift along the beam provides the fine laser wavelength tuning within the free spectral range of the external cavity. Accordingly, it is possible to consider a scheme in which the optical feedback can be set at an optimum level by appropriately setting the VHG in the external cavity. The proper VHG design provides the additional degree of freedom in optimization of laser parameters.

5. Tuning the diode laser with VHG external cavity

In our experiments, we have used the volume holographic grating recorded in the original photopolymer composition developed in the Institute of Physics PPC-488 [12]. The VHG active layer thickness is 33 µm, an average refractive index is 1.56 with amplitude modulation of the refractive index 0.00667, and the spatial modulation period of the refractive index of 0.92 µm [13]. Fig. 7 shows redistribution of the laser output intensity between output laser (1) and diffracted (2) beams.

The intensity of retro reflected by external cavity mirror beam as parameter of the feedback efficiency is shown, too (3). The operation point of optimal optical feedback with the stable operation of ECDL is marked at the detuning angle near 1.25° and corresponds to the optical feedback efficiency near 10%.

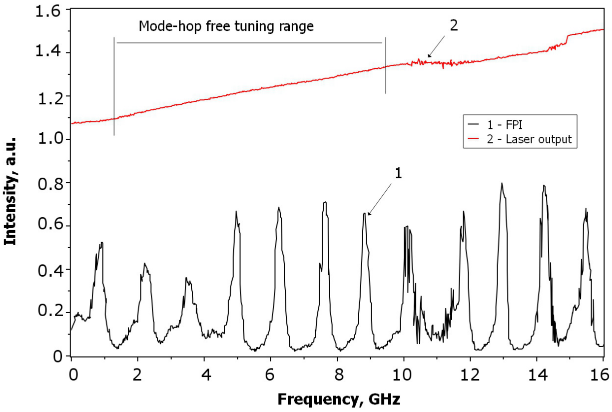

Fig. 8. Frequency tuning of ECDL based on VHG.

In our experiment, we have used the diode laser HLDP-650-A-5-02 with non-AR front facet. In this regard, to increase the range of mode-hop free frequency tuning range of the laser it was necessary to change the length of the external resonator and the position of longitudinal modes of a laser diode crystal simultaneously. This was achieved by applying a voltage to the piezoelectric transducer of cavity mirror. The applied voltage was proportional to the laser diode injection current. ECDL emission was analyzed with a Fabry–Perot etalon within the free spectral range 1.33 GHz. The results are depicted in Fig. 8. It is seen that mode-hop free tuning range of ECDL with VHG reaches 8 GHz.

6. Conclusions

The diode lasers with external cavities are widely used in laser cooling, spectroscopy, metrology, atomic gravimetry, interferometry, environmental control, atomic clocks, quantum key cryptography, *etc*. The laser sources having both narrow radiation spectra and high laser output power are very attractive for many applications. The frequency-selective optical feedback in the diode laser external cavity containing VHG can be finely tuned to the optimal grade with the ability to enhance the laser output. The VHG containing cavities are rather promising for application in the design of power diode lasers with narrow spectral line of output radiation. The mode-hope free tuning of ECDL with VHG has been demonstrated and the temperature dependence of gain peak spectral position of power diode laser bar has been measured.

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