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Study of the emission spectra of a 1320-nm semiconductor disk laser and its second harmonic

K.S. Gochelashvili, S.I. Derzhavin, O.N. Evdokimova, I.O. Zolotovskii, S.V. Podmazov

Abstract. **The spectral characteristics of an optically pumped external-cavity semiconductor disk laser near λ = 1320 nm are studied experimentally. Intracavity second harmonic generation is obtained using an LBO nonlinear crystal. The output power at a wavelength of 660 nm in the cw regime was 620 mW, and the peak power in the pulsed regime was 795 mW.**

Keywords: *semiconductor disk laser, second harmonic generation, vertical-external-cavity lasers, optical pumping.*

1. Introduction

Although only a little more than half of a century has passed since Russian scientists discovered the possibility of lasing in semiconductor structures [1], today semiconductor lasers are already used almost in all fields of human activity.

For the last two decades, semiconductor disk lasers (SDLs), which are also known as vertical-cavity semiconductor lasers [2, 3], have begun to be widely used in the creation of high-power semiconductor lasers with a high beam quality. The symmetry of the output beam of SDLs, whose quality is better than the beam quality of semiconductor lasers of a planar waveguide structure [4], and the absence of a thermal lens due to a small active layer thickness are the distinguishing features of this class of lasers. The vertical-cavity semiconductor lasers can differ from each other by the type of pumping (optical [5], electronic [6], or injection (current) [7]) and by the presence [4–5] or absence [7] of an external cavity. External-cavity optically pumped SDLs combine a high power of planar semiconductor lasers and a high beam quality of SDLs without an external cavity. That is why external-cavity SDLs are leaders in the output power and beam quality for one element [8]. The existence of an external cavity makes it possible to include in the optical scheme various elements, such as nonlinear crystals, optical filters, and saturable absorbers. Like all semiconductor lasers, SDLs can emit in a wide wavelength range due to replacement of the active element material, which is impossible in the case of solid-state and other types of lasers. In addition, the wavelength range of external-cavity optically pumped SDLs can be extended by including nonlinear crystals into the cavity. Today, the wavelength range of vertical-cavity optically pumped SDLs extends from 0.244 to 5 μm [9–10].

The field of application of optically pumped SDLs is very wide [11] and includes quantum cryptography, flow cytometry, medical diagnostics and therapy, fine arts, forensic analysis, and metrology. Disk lasers are also used for optical pumping of, for example, ceramic lasers [12].

The main goal of our investigations was to study the spectral characteristics of external-cavity optically pumped SDLs operating at a wavelength of 1320 nm in a pulsed regime. One more purpose was to study the generation of the second harmonic of this disk laser with a power of several watts in both cw and pulsed regimes. This work is the first stage of investigations aimed at creating a radiation source for quantum cryptography and selective laser photoionisation of isotopes. The main requirements to lasers for isotope separation are a several-watt power in both pulsed and cw regimes (depending on the separation scheme), stability, and narrow-band emission. External-cavity optically pumped SDLs completely satisfy these requirements because they have high radiation power in a wide wavelength range while the existence of an external cavity allows one to use etalons to achieve a narrow spectral linewidth.

2. Experimental setup

The scheme of the experimental setup for measuring spectral characteristics of a disk laser in a pulsed regime is shown in Fig. 1. This figure also schematically shows the structure of the semiconductor disk chip.

The active medium of the disk chip consisted of five AlGaInAs/InP quantum wells grown by low-pressure gas phase deposition. The distributed Bragg mirror consisted of 35 pairs of quarter-wave AlGaAs/GaAs layers grown by molecular-beam epitaxy. The active medium and the mirror were attached to each other by wafer fusion [13]. A diamond plate (heat sink), which was antireflection coated for the fundamental laser wavelength, was attached to the active medium by capillary bonding [14]. This construction was pressed to a copper heat sink through indium foil, while from the other

K.S. Gochelashvili, S.I. Derzhavin, O.N. Evdokimova A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: knst@kapella.gpi.ru, derzh@kapella.gpi.ru;
I.O. Zolotovskii Ulyanovsk State University, ul. L. Tolstogo 42, 432017 Ulyanovsk, Russia; e-mail: rafzol.14@mail.ru;
S.V. Podmazov Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudny, Moscow region, Russia; e-mail: sergei.podmazov@mail.ru

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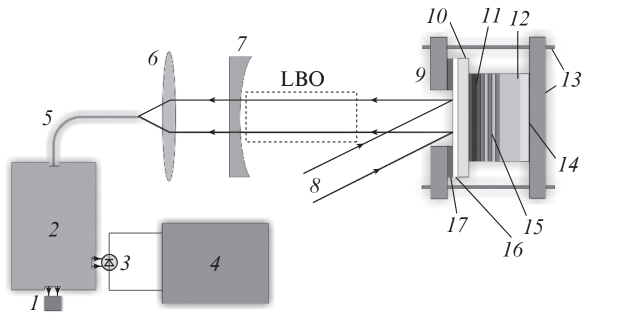

Figure 1. Scheme of the experimental setup:
(*1*) chamber; (*2*) monochromator; (*3*) photodiode; (*4*) oscilloscope; (*5*) optical fibre; (*6*) focusing lens; (*7*) output mirror (R = 100 mm); (*8*) pump beam (λ = 960 nm); (*9*) copper heat sink; (*10*) diamond heat sink; (*11*) active medium; (*12*) substrate; (*13*) clamp and mount; (*14*) Teflon gasket; (*15*) Bragg mirror; (*16*) antireflection coating; (*17*) indium foil.

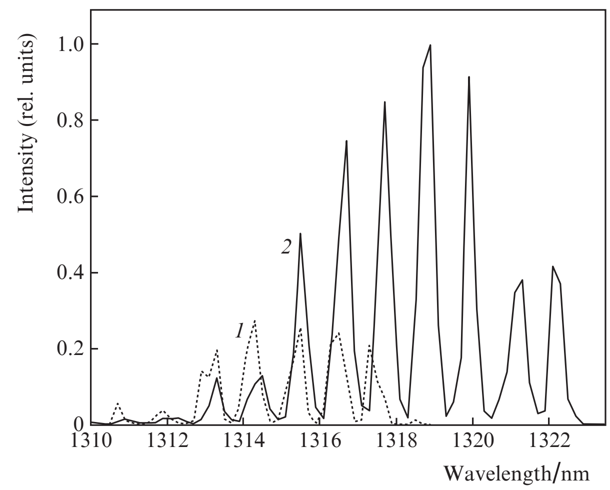

Figure 2. Disk laser spectra at pump powers of (*1*) 14.1 and (*2*) 21.2 W.

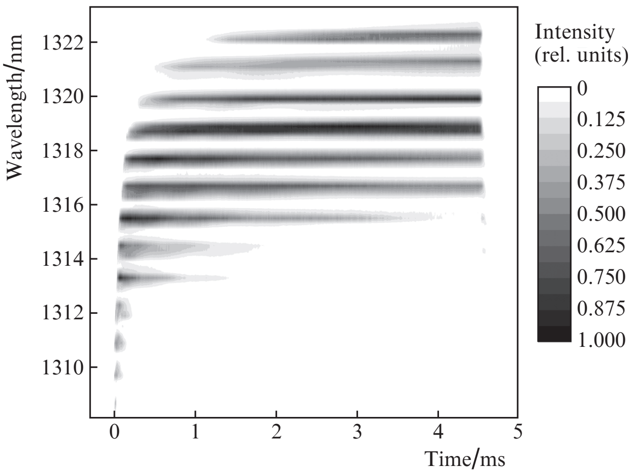

Figure 3. Time dependences of the laser spectrum upon pulsed pumping.

side it was fixed by an aluminium clamp with a Teflon gasket. The layer temperature was stabilised using water cooling through a micro-channel copper heat sink. The water temperature was kept constant at 19 °C.

For optical pumping at a wavelength of 960 nm, we used a fibre-coupled laser diode module with a power of 24 W. The pump radiation was focused by a lens system on the disk chip into a spot 300 μm in diameter. The external cavity 50 mm long was formed by an external spherical mirror with a curvature radius of 100 mm and transmissions of 12% at a wavelength of 1320 nm and 77.3% at the second-harmonic wavelength and by a distributed Bragg mirror on the semiconductor substrate.

The spectral characteristics of the laser radiation were studied using an MDR-23 monochromator. A germanium photodiode, which recorded the spectrum of the pulsed radiation near the wavelength 1320 nm, was placed at one exit of the monochromator. A Mintron MS-168P camera, which was used to study the second harmonic spectrum, was placed at the other exit of the monochromator. The average laser power was measured by a COHERENT EMP-2000 calorimeter.

The second harmonic was generated in an LBO nonlinear crystal measuring 4×4×15 mm in the position of the I-type critical phase matching (θ = 90°, φ = 0°). The position of the crystal in the cavity is shown by dashed lines in Fig. 1. The faces of the LBO crystal were antireflection coated for wavelengths of 1320 and 660 nm.

3. Experimental results

Figure 2 shows the fundamental spectra of the semiconductor disk laser for pump powers of 14.1 and 21.2 W. With increasing pump power, the laser spectrum becomes broader and shifts to longer wavelengths due to an increase in the active element temperature, which is typical for all semiconductor lasers. The spectrum contains holes with a period of 1.1 nm caused by the diamond plate, which, despite the antireflection coating on it, is a parasitic Fabry–Perot etalon.

The spectral characteristics of the laser radiation were studied in a pulsed regime under optical pumping by pulses with a duration of 5 ms and a repetition rate 15 Hz. Figure 3 presents the disk laser spectrum recorded for the entire pulse duration. Time is measured from the beginning of lasing. The obtained data show that the thermal equilibrium of the active element is achieved for the first 3.5 ms. After this, the spectrum remains unchanged to the end of the pump pulse. Clear peaks are seen in the regions of 1314.3 and 1315.5 nm at the end of the pulse. This fact is demonstrated in more detail in Fig. 4, which simultaneously shows a pump pulse and a laser pulse at a wavelength of 1314.3 nm. A peak in the laser pulse is observed at the middle of the trailing edge of the pump pulse. It should also be noted that the spectral lines in the range 1316–1324 nm disappear at the very beginning of the trailing edge of the pump pulse, i.e., before the appearance of the peak. This behaviour of the spectrum testifies that, during the pump pulse fall, the active medium cools enough to exhibit a short-wavelength shift of the laser spectrum. At the same time, the pump power is still sufficient for lasing.

The peak output power of the laser in the pulsed regime at a wavelength of 1320 nm under a peak pump power of 24 W was 860 mW. In the cw regime, the output power at the same wavelength and an average pump power of 24 W was 720 mW. The difference in the powers is explained by insufficient heat removal from the active medium.

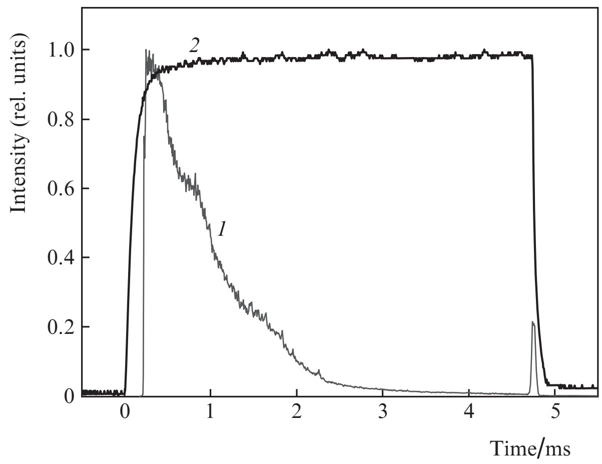

Figure 4. Laser pulse at a wavelength of 1314.3 nm (*1*) and pump pulse (*2*).

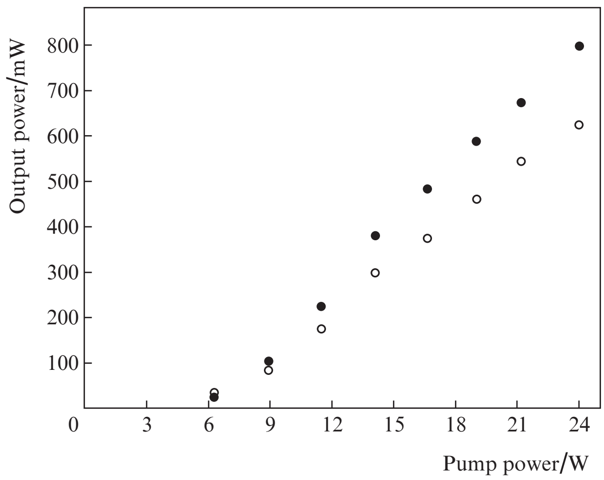

Figure 6. Dependences of the second harmonic (λ = 660 nm) power of the SDL on the pump power in the pulsed (●) and cw (○) regimes.

Figure 5 shows the spectrum of the second harmonic of the SDL. The periodicity of oscillations in the spectrum is retained. Due to parasitic illumination of the camera, we failed to completely resolve some peaks in the spectrum.

The dependences of the output second harmonic power on the pump power in the pulsed and cw regimes are presented in Fig. 6. The maximum achieved power in the cw regime is 620 mW. With an output mirror antireflection coated for a wavelength of 660 nm, the output power increases to 770 mW. This power is emitted by the LBO crystal in one direction, which means that, if we deposit a coating completely reflecting the second harmonic radiation (660 nm) and transparent for the SDL radiation (1320 nm) on one surface of the LBO crystal, the output power through one face of the crystal can be increased to at least 1.5 W.

Thus, the study of the spectral characteristics of the optically pumped external-cavity semiconductor disk laser in the pulsed regime revealed an instability of the spectrum during the pulse. The presence of a diamond plate (heat sink) leads to the parasitic etalon effect, which must be taken into account in further attempts to obtain narrow-band lasing. As to the second aim of our investigations, we obtained second harmonic generation using intracavity frequency conversion in an LBO nonlinear crystal. The cw output power at a wavelength of 660 nm was 620 mW, and the peak power in the pulsed regime was 795 nm.

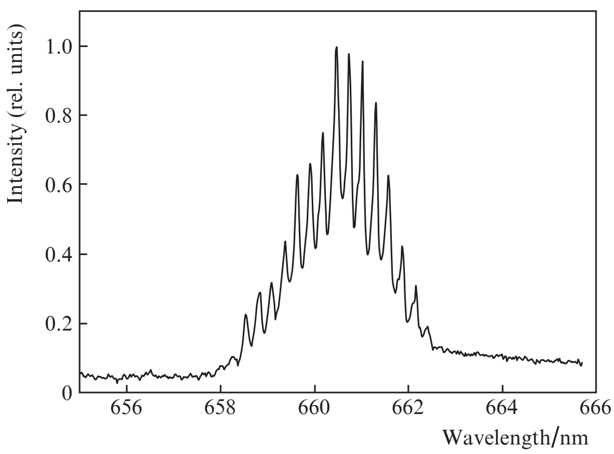

Figure 5. Spectrum of the second harmonic of the SDL.

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