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Vertical-external-cavity surface-emitting 625-nm laser upon optical pumping of an InGaP/AlGaInP nanostructure with a Bragg mirror*

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***Abstract*.** **Pulsed lasing is obtained in a multilayer quantum-well InGaP/AlGaInP structure in a cavity with an external mirror and a Bragg AlAs/AlGaAs mirror pumped by the 532-nm second harmonic from a diode-pumped *Q*-switched Nd:YAG laser. Lasing is obtained at the TEM_{00} fundamental transverse mode of the cavity at a wavelength of 625 nm. The pulse beam power was 3.1 W and the radiation divergence achieved a diffraction limit of 10 – 12 mrad for 5-ns pulses with a repetition rate of 6 kHz.**

Keywords: *semiconductor laser, external cavity, GaInP/AlGaInP nanostructure, optical pumping.*

1. Introduction

In this paper we studied a laser, which is called a vertical-external cavity surface-emitting laser (VECSEL) or a semiconductor disk laser. The optical cavity of this laser consists of a semiconductor multiple quantum-well (MQW) structure, providing optical gain upon optical (or different) pumping, and a plane (M1) and a spherical (M2) cavity mirrors (Fig. 1). Such a laser can find many practical applications [1, 2] because it provides the high output power and high conversion efficiency of the pump energy to light inherent in semiconductor lasers, in conjunction with the high quality of the laser beam inherent in external cavity lasers. The output radiation of the laser is diffraction-limited and is almost completely concentrated in the TEM_{00} fundamental transverse mode. In addition, a long cavity of length 50 – 100 mm opens up the possibility for the efficient intracavity second harmonic generation.

The potential possibilities of a VECSEL were demonstrated for the first time in paper [3], where 0.52 W was obtained in the TEM_{00} mode at 1004 nm in the cw regime. The authors of [3] used a 808-nm diode-pumped InGaAs/AlGaAs MQW active medium and a Bragg AlAs/GaAs mirror as a highly reflecting mirror. Later (see, for example, [4 – 6]), the output power of the laser was considerably increased together with retaining the high quality of the laser beam.

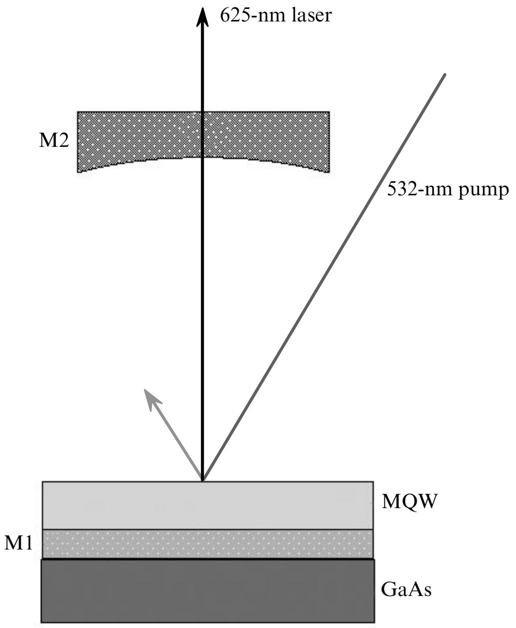

Figure 1. Optical scheme of an external cavity laser.

The second harmonic generation (SHG) was realised in many papers, and radiation in the red, green, blue, and UV spectral regions was obtained [6 – 8]. Thus, 1.1 W was obtained at 675 nm in an InGaP/InGaAlP MQW laser with a Bragg AlGaAs/GaAs mirror pumped by the cw 532-nm second harmonic from a Nd laser. The intracavity SHG of this radiation produced 120 mW of the 337-nm UV radiation.

The mathematical model of VECSEL was proposed in paper [9], where a review of the main experimental studies of this laser performed until 2006 is also presented. A review of further studies can be found in paper [6].

In this paper, we present the results of our investigations of a VECSEL in which, as in the laser in [8], the active medium is an InGaP/InGaAlP MQW structure and a distributed Bragg mirror is a multilayer AlGaAs/AlAs structure. Unlike [8], we used another composition of solid InGaP solutions in quantum wells and InGaAlP in barriers and obtained lasing at 625 nm, which is a step forward in the

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solution of the problem of the development of semiconductor disk lasers emitting at wavelengths shorter than 635 nm [6]. In addition, we used pulsed pumping by the 532-nm second harmonic of a Nd laser. The pulse regime is of interest at least at the stage of studying the properties of the laser because it eliminates restrictions caused by the heating of the active medium and opens up the possibility to increase the output power and the second harmonic generation efficiency. In addition, this regime provides important information on the dynamics of the transient process of the increase in the intracavity field, when the mode gain can be considerably greater than that in the steady state.

2. Experimental

A distributed AlGaAs/AlAs Bragg reflector (DBR) and a quantum-well InGaP/InGaAlP structure were grown on a GaAs substrate in a single MOCVD technological process. The calculated reflectance at the interface with InGaAlP was no less than 99.8 % at 625 nm. A multiple quantum-well structure is a periodic sequence of 8-nm-thick InGaP quantum wells (QWs) and 183-nm-wide gap InGaAlP barriers (Fig.2). The period 191 nm is selected to coincide with the InGaAlP laser wavelength, so that all QWs could be located near the antinodes of the standing wave of the cavity. The total MQW thickness was about 5 μm (26 periods of 191 nm).

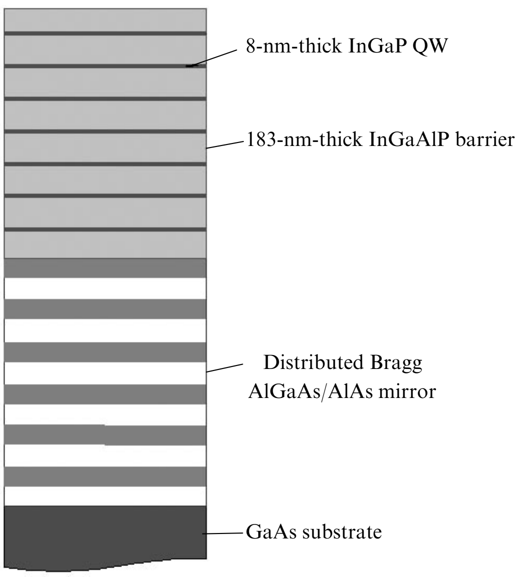

Figure 2. Nanostructure scheme.

The output mirror M2 of the cavity was a glass disk with the radius of curvature of the spherical surface equal to 50 mm and a reflection coating had the reflectance of 98.5 % at 625 nm. The cavity length was varied within ±10 % near 45 mm, the calculated diameter of the TEM_{00} cavity mode (at the 1/e field intensity level on the cavity axis) on the MQW surface being 75 μm.

The multilayer quantum-well structure was pumped by the second harmonic from a diode-pumped *Q*-switched Nd : YAG laser with an acoustooptic switch [10]. The 532-nm laser pulse duration was 10 – 20 ns depending on the Nd : YAG laser pumping level; the pulse repetition rate could be varied from 2 to 20 kHz. The angle of incidence of the pump beam on the MQW surface was 30°, the laser spot size being 75 – 100 μm.

The pulse shape and pump and laser output powers were measured with FEK 29 and FEK 22 vacuum photocells and a TDS 5054B digital oscilloscope with an accuracy better than 1 ns in time and ±30 % in the absolute power.

Note that the photon lifetime τ_{ph} in the cavity determined by radiation losses was ~ 20 ns for the mirror reflectances indicated above. Therefore, the conditions of quasi-stationary lasing are definitely not fulfilled in the laser under study. In this case, amplification can considerably exceed cavity losses, and the growth dynamics of the intensity of the transverse modes in the cavity is not known *a priori* and it is not clear whether the TEM_{00} mode will be dominant.

3. Results

The visual observations of the far-field illumination of a screen show that red radiation becomes noticeable when the pump power is about 40 W. As the pump power is increased up to 500 W, the radiation brightness increases monotonically, while the radiation intensity distribution in the form of a circular spot, which is typical for a Gaussian beam with the radiation pattern angle of width 10 – 12 mrad, remains unchanged. The latter corresponds to the TEM_{00} mode of the cavity with the radiation pattern width 7.5 mrad (taking into account refraction in the substrate of the output mirror of the cavity). A more complicated shape of the illumination spot was observed when the adjustment of the external mirror of the cavity was not accurate enough, the pump spot was strongly asymmetric or inhomogeneous, and also in the case of local defects on the MQW surface. However, by adjusting the optical elements of the laser more accurately or performing the parallel displacement of the MQW, it was always possible to provide lasing at the fundamental cavity mode (Fig. 3).

The laser emission spectrum consists of one line at 625 nm of width no more than 0.5 nm. The laser line recorded with a spectral resolution of 0.5 nm and a relative intensity resolution of 1/200 reveals no structure.

The lasing dynamics is illustrated by the oscillograms of the pump and laser pulses at different pump powers (Fig. 4).The error in synchronisation of the pump and laser pulses does not exceed 1 ns. Red radiation appears at the trailing edge of the pump pulse. As the pump power is increased from 70 to 440 W, the delay of the laser pulse with respect to the pump pulse decreases from 8 to 6 ns, while the laser pulse duration almost does not change, being ~ 5 ns, which is considerably smaller than the photon lifetime in the cavity (20 ns).

Figure 5 shows the dependence of the laser beam power on the pump power at a pulse repetition rate of 6 kHz. The experimental points are the result of the automatic averaging of the pulse amplitude for the time 0.1 s (approximately 500 pulses) and the error bars give the root-mean-square deviation of the laser pulse amplitude from the average value. The solid curve is the subjective approximation of these points. The scatter of experimental points with respect to the curve is caused by the long-term (for a few minutes) instability of the pump pulse amplitude.

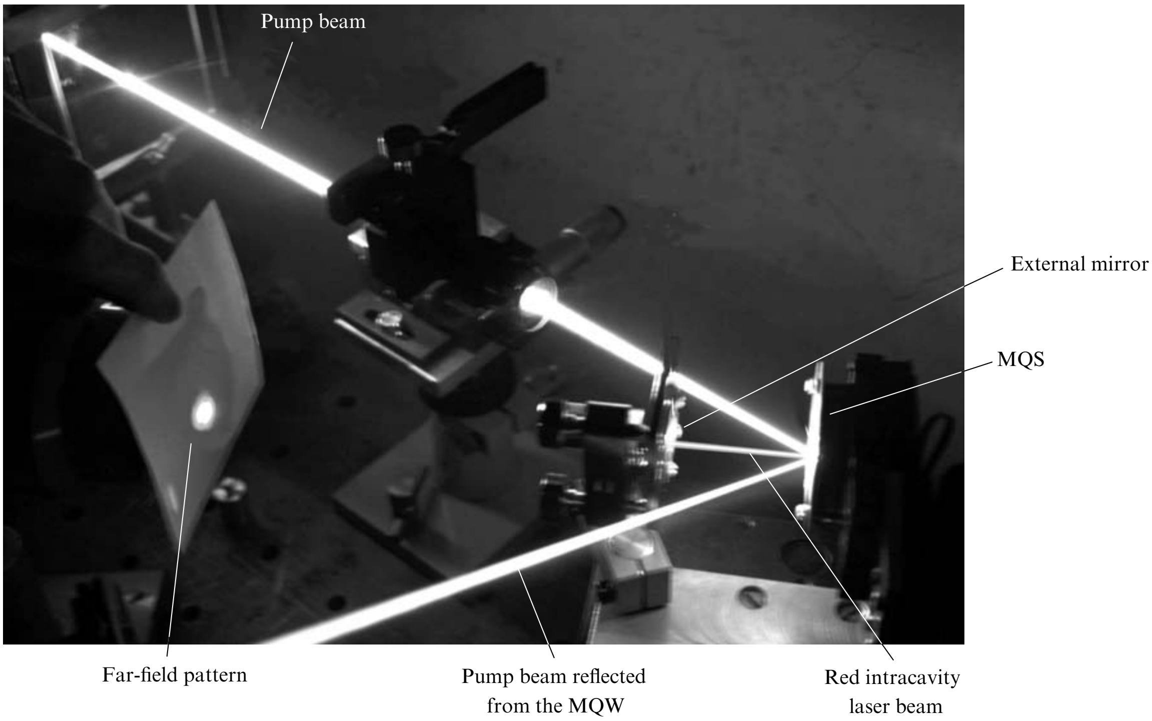

Figure 3. Photograph of the working model of the laser.

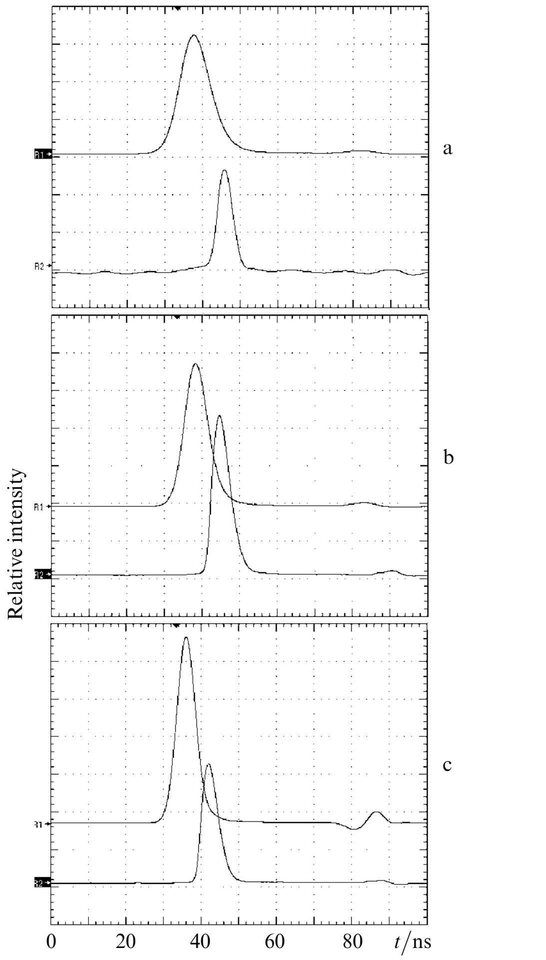

Figure 4. Oscillograms of pump pulses (the upper curves) and laser beams (the lower curves) for pump pulse amplitudes 70 (a), 200 (b), and 440 W (c).

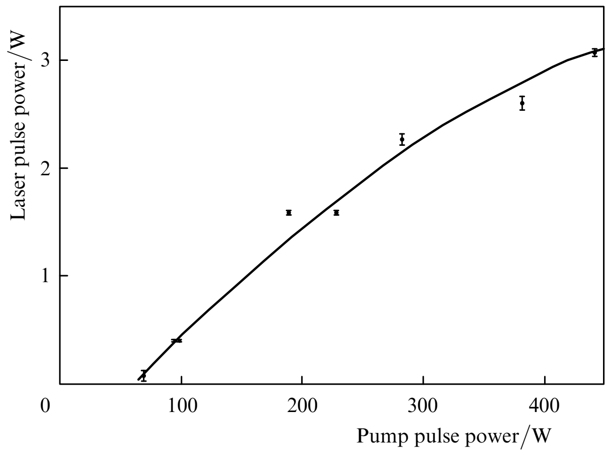

Figure 5. Dependence of the laser beam power on the pump power at a pulse repetition rate of 6 kHz.

The pulsed power of the laser pumped by 440 W achieved 3.1 W, while the slope efficiency monotonically decreased from 1.2 % at the initial part of the characteristic down to 0.5 % for the maximum pump energy.

4. Discussion of the results

A specific feature of an external cavity semiconductor laser compared to other solid-state lasers is the short excited-state lifetime. The typical lifetime (1 ns) of an electron–hole pair in semiconductors is considerably shorter than $\tau_{ph} = 20$ ns in the cavity under study. The calculation shows that the maximum gain per round-trip transit in the cavity is $G \approx 0.25$. In the case of the isotropic spontaneous emission of a MQW, only 10^{-6} of photons are emitted in the TEM_{00} mode. In addition, $\sim 10^{-2}$ of photons of the initial spontaneous spectrum are emitted in the laser line. In the case of quasi-steady-state lasing, a fraction of photons emitted within the narrow TEM_{00} line achieves unity after N round-trip transits in the cavity, where N is determined by the expression $\exp(GN) = 10^8$. Therefore, the lasing rise time t_1 should be equal to $2LN/c$, i.e. $t_1 \approx 20$ ns for $L = 4.5$ cm. The real value of t_1 can be even greater because the gain G can be smaller than 0.25.

The delay (6 – 8 ns) of the laser pulse with respect to the pump pulse measured in experiments is smaller than t_1, i.e. we are dealing with nonsteady-state lasing. During the time interval from the pump pulse onset up to t_1, a considerable part of the pump power is spent for spontaneous emission, which is one of the reasons for a low lasing efficiency. Another reason is probably high intracavity losses. Indeed, the laser pulse decay time (4 ns) is considerably smaller than $\tau_{ph} = 20$ ns. Intracavity absorption can be caused by the nonuniform pumping of QWs due to the non-optimal absorption of pump radiation in barrier layers.

The nonlinearity of the output characteristic of the laser (Fig. 5) is caused, in particular, by the shortening of the pump pulse with increasing its amplitude. The pump pulse shortening at the unchanged delay time of the laser pulse leads to the shift of the laser pulse to the region of lower pump powers, resulting in the additional decrease in the lasing efficiency.

The good selection of the transverse cavity modes was achieved due to the careful matching of the pump spot size with the TEM_{00} mode diameter.

The qualitative interpretation of experimental data presented here is confirmed by numerical calculations based on the mathematical model [9].

5. Conclusions

We have obtained lasing in the InGaP/AlGaInP MQW at a wavelength of 625 nm with an output power of 3 W upon pulsed pumping. Lasing occurs at the fundamental transverse cavity mode with the diffraction-limited divergence. The obtained results open up the favourable possibilities for increasing the output laser power by optimizing the cavity Q factor and for intracavity second harmonic generation of UV radiation at ~ 312 nm.*

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*New results obtained before May of 2009, in particular, the intracavity second harmonic generation at 312.5 nm were reported at the 7th Belarus – Russia Seminar on Semiconductor Lasers and Systems Based Them, 1 – 5 June, 2009, Minsk, Belarus (*proofreading addition*).