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Linewidth study of MBE-grown wafer-fused single-mode 1.55 μm VCSELs

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In this work static and spectral characteristics of 1.55 μm range vertical-cavity surface emitting lasers with active area based on InGaAs/InGaAlAs quantum wells were studied. Efficient single-mode operation was demonstrated through the fundamental mode with a side mode suppression ratio of more than 25 dB, additionally, laser emission was polarized along the long axis of the buried tunnel junction mesa and the suppression ratio of the orthogonally polarized mode more than 20 dB was achieved. During the studies of the laser emission linewidth the emission spectral line was narrowed down to $\sim$ 30−35 MHz as the output optical power increased up to $\sim$ 1 mW (operating current more than 5 mA). At an output optical power of more than 2.5 mW, a broadening of the spectral line was observed, due to a rise of the laser internal temperature. The corresponding linewidth broadening factor lies in the range of 3.3−4.4 depending on the value of the population inversion factor.

Keywords: VCSEL, polarization, linewidth, α-factor.

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Recently, there has been a significant increase in interest in the development and creation of long-wavelength vertically emitting lasers (VCSELs), which can be used not only for integrated photonics and the creation of a new generation of optical interconnects for data storage and processing systems, but also for the creation of various recognition systems objects and gas sensors [1]. One of the promising directions for creation of VCSELs with emission in spectral range 1.55 μm is the combination of an optical microresonator containing an active region based on a system of InAlGaAs/InP materials with distributed Bragg reflectors (DBR) with high reflectivity and thermal conductivity [2]. As part of such a solution, two approaches can be distinguished, one is based on hybrid integration with hybrid metal-dielectric DBR with a high contrast of the refraction index of layers (hereinafter referred to as HI-VCSEL) [3], and the second — on an intermolecular bonding with semiconductor AlGaAs/GaAs DBRs using wafer fusion technology (hereinafter WF-VCSEL) [4,5]. We have recently shown the fundamental opportunity of creating effective WF-VCSEL based on thin strained InGaAs/InAlGaAs quantum wells (QWs) using molecular-beam epitaxy (MBE) [6]. Despite the fact that the laser emission linewidth is an important parameter for the design and creation of fiber data transmission systems or gas sensors, only a few works can be identified that are devoted to this problem [7,8]. This work presents the results of studies of the emission linewidth of single-mode WF-VCSELs based on InGaAs/InAlGaAs QW in the spectral range 1.55 μm.

The design of the studied WF-VCSEL is a vertical optical microresonator placed between two AlGaAs/GaAs DBRs, in which the injection of charge carriers occurs through intracavity n-InP contacts and a composite n^+−InGaAs/p^+−InGaAs/p^+−InAlGaAs tunnel junction (TJ). The active region consists of ten strained $In_{0.74}Ga_{0.26}As$ QW separated by lattice-matched barriers $In_{0.53}Al_{0.16}Ga_{0.31}As$. Current and optical confinements are implemented within the concept of an buried tunnel junction (BTJ), by forming TJ with a diameter of 6 μm in InGaAs layers, followed by overgrowing with an n-InP layer (BTJ mesas of elliptical shape are formed [9]). A more detailed description of the design and features of the manufacturing technology WF-VCSEL are given in the work [6].

The watt-ampere and spectral characteristics measured in continuous operating mode WF-VCSEL are shown in Fig. 1. The WF-VCSEL under study demonstrated lasing near 1.55 μm with a threshold current of 1.7 mA and a maximum differential efficiency of more than 0.32 W/A. At injection currents over 10 mA, the self-heating effect appeared, limiting the maximum optical power. The study of polarization characteristics showed the dominance of the polarization direction along the long axis of the mesa BTJ in the entire range of pumping currents with a suppression coefficient of more than 20 dB. The analysis of the laser emission spectra WF-VCSEL revealed the

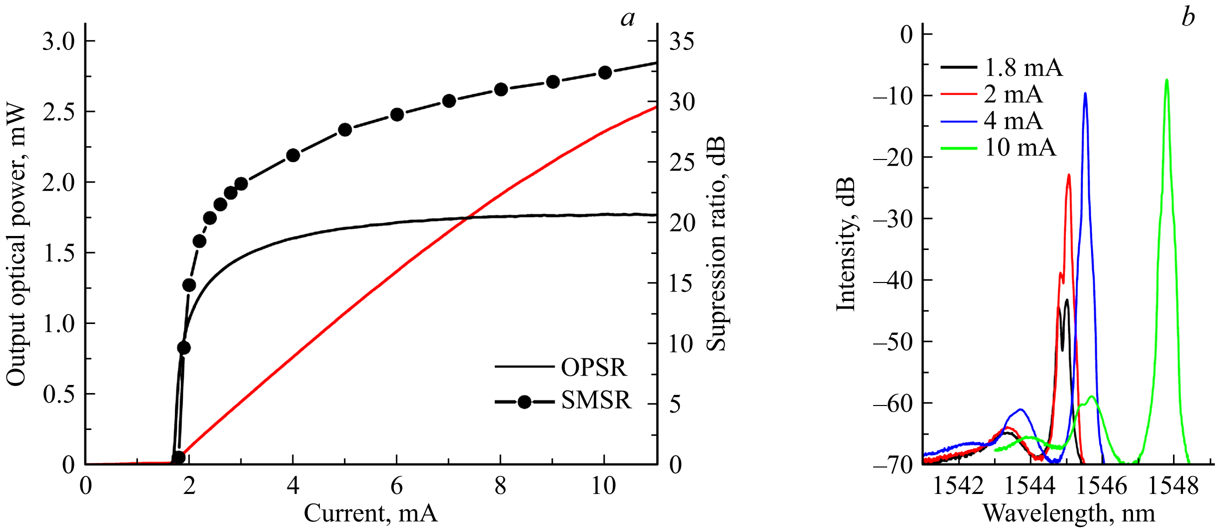

Figure 1. WF-VCSEL: (*a*) Dependences of the output optical power, orthogonal polarization suppression ratio (OPSR) and side mode suppression ratio (SMSR) on the pumping current; (*b*) optical spectra of laser radiation at different pumping currents.

predominance of the long-wave mode with a suppression coefficient for the side mode of over 20 dB.

As is known, the spectral linewidth of the emission of semiconductor lasers $\Delta\nu_L$ is described by the modified Schawlow-Townes-Henry equation [10]:

$$\Delta\nu_L = \Delta\nu_0 + \frac{e n_{sp} \eta_{SE} v_g^2 (T_m + A_{int})^2}{4\pi P \eta_{int}} (1 + \alpha^2),$$

where $\Delta\nu_0$ — residual line width, n_{sp} — population inversion factor, v_g — group velocity, $h\nu$ — electron charge, η_{SE} — differential efficiency, η_{int} — current injection efficiency, T_m — output losses, A_{int} — internal optical losses, P — output optical power, α — linewidth broadening factor.

Figure 2 shows the results of studying the emission linewidth WF-VCSEL at room temperature using a Thorlabs SA30-144 scanning Fabry-Perot interferometer. It should be noted that a chemical power supply was used as the power source to prevent unwanted emission line broadening due to power supply noise, and a Thorlabs optical isolator was installed in front of the interferometer to suppress the effect of optical feedback IO-2.5-1550-VLP . With an increase in the output optical power, the spectral emission line WF-VCSEL narrows at a rate of ~ 7.8 MHz/mW in accordance with the Schawlow-Townes-Henry theory (section A). However, at powers more than 1 mW (operating current over 5 mA), saturation is observed, and at powers more than 2.5 mW (operating currents over 10 mA) broadening of the emission line with increasing output optical power WF-VCSEL (section B). As a result, the minimum value of the spectral line width lies in the range 30–35 MHz.

It should be noted that anomalous behavior of the emission linewidth was previously observed both for the near-IR VCSEL [11] and for the long-wavelength HI-VCSEL [4]. Moreover, as the external temperature increases, this effect begins to manifest itself at a lower output power [7]. In this regard, we assessed the internal temperature of the VCSEL using data of the wavelength shift with the temperature $\partial\lambda/T \sim 0.09$ nm/K and the wavelength shift with the dissipated electrical power $\partial\lambda/P_{diss} \sim 0.18$ nm/mW. As shown in Fig. 2, in section A we can neglect the change in the internal temperature of the laser and, therefore, determine the parameters $\Delta\nu_0$ and α. Internal optical losses and carrier injection efficiencies were determined within the analysis of differential efficiency with dependence on output losses by analogy with works [12,13]. In the case of VCSEL, it is difficult to adequately determine the population inversion factor, so the α factor can be estimated in the ~ 3.3–4.4 range when the n_{sp} value varies from 2 to 1.2 [10,14]. The residual emission linewidth reaches ~ 20 MHz and is apparently caused by mode competition (in this case, modes with orthogonal polarization) or flicker noise (charge carrier density fluctuation) and requires further research [8]. In section B , the internal temperature of the WF-VCSEL begins to rise sharply as the output power increases (laser self-heating), which leads to a drop in the differential gain [8] and, in combination with the effect of gain saturation with current, to an increase in the α-factor [15].

In general, the obtained values of the α factor and the minimum width of the spectral line of emission correlate with the data for HI-VCSEL based on InAlGaAs QW [4], monolithic VCSEL based on InAlGaAs QW [16] and WF-VCSEL based on InGaAsP QW [17].

A comprehensive analysis of the characteristics of the WF-VCSEL lasing at 1.55 μm based on strained InGaAs/InAlGaAs QWs was carried out. Devices with a mesa diameter of TJ 6 μm demonstrated a single-mode lasing with a fixed direction of radiation polarization. As the output optical power increases, an inversely proportional decrease

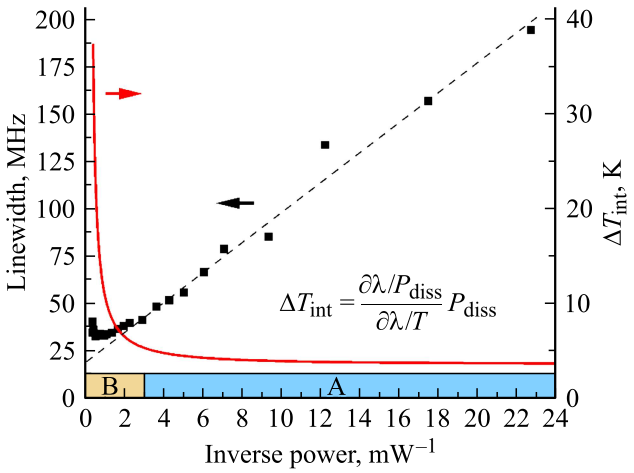

Figure 2. Dependence of the emission linewidth and internal temperature on the reciprocal of the output optical power. The dashed line indicates the approximation of the linear portion of this dependence.

in the laser radiation linewidth is observed. However, an increase in the internal temperature of the laser due to the self-heating effect limits the minimum linewidth at the level $\sim 30-35$ MHz, and at increased operating currents of more than 10 mA leads to a sharp broadening. In the range of operating currents, when the self-heating effect can be neglected, the α factor was assessed.

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Conflict of interest

The authors declare that they have no conflict of interest.

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