Quantum Electronics **31** (1) 35 – 38 (2001)

PACS numbers: 42.55.Px; 42.60.Da; 42.82.Et
DOI: 10.1070/QE2001v031n01ABEH001887

Tunable wide-aperture semiconductor laser with an external waveguide – grating mirror

B N Zvonkov, K E Zinov'ev, D Kh Nurligareev,
I F Salakhutdinov, V V Svetikov, V A Sychugov

***Abstract*. An external cavity with a waveguide – grating mirror (WGM) is proposed for a wide-aperture semiconductor laser. The emission spectra of a laser diode in the cavity were studied for a collinear and noncollinear incidence of radiation on the WGM. The substantial (down to 0.1 nm) narrowing of the emission spectrum was obtained, and a continuos tuning of laser radiation in the range from 10 to 18 nm was demonstrated.**

***Keywords*:** *wide-aperture laser diode, external cavity, waveguide – grating mirror.*

1. Introduction

At present, high-power wide-aperture semiconductor lasers attract great attention because of their possible applications in many areas – from satellite information systems to home electronic devices. However, a complicated mode structure and a large divergence of emission of such lasers hinders their application in most cases. For this reason, researchers recently have concentrated their attention on the improvement of laser radiation characteristics.

The above disadvantages of wide-aperture semiconductor laser diodes (LDs) are mainly caused by a filamentation – the transverse spatial modulation of the optical flux intensity, for suppression or stabilisation of which some designs of LDs were proposed (see, for instance, [1 – 3]). However, a realisation of such LD designs is related to strong complication of fabrication technology of semiconductor structures. At the same time, it seems possible to suppress the filamentation or to increase substantially the threshold of the filamentation in conventional LDs with broad stripe contacts by using an external cavity of a special design, for instance, a cavity with a corrugated waveguide used as an output or internal selective mirror [4, p. 89].

In this paper, we studied a laser based on a wide-aperture LD with an external cavity containing a waveguide – grating mirror (WGM) with anomalous reflection of light. The essence of the effect of anomalous light reflection is that upon excitation of a corrugated waveguide by a light beam, the beam suffers a total internal reflection [5, 6]. The reflection is observed in a very narrow spectral range (for a constant angle of incidence) or in a narrow angular range (for a given radiation wavelength). Therefore, such a mirror inside a cavity can provide lasing in a narrow spectral range. In addition, because this mirror is a waveguide mirror, it provides a geometric expansion of the reflected light beam, resulting in the improvement of the spatial coherence of laser radiation and, finally, in the improvement of the conditions for the in-phase operation of the active medium. Thus, the use of a WGM reduces the modulation of the optical flux inside a LD.

The matching diagram of the wave vectors (Fig. 1) upon excitation of a mode of a waveguide mirror is described by the equation

$$|\boldsymbol{k}_{\rm m}|^2 = |\boldsymbol{k}_{\rm i}|^2 + |\boldsymbol{k}_{\rm g}|^2 + 2|\boldsymbol{k}_{\rm i}||\boldsymbol{k}_{\rm g}|\cos\varphi, \quad (1)$$

where $\boldsymbol{k}_{\rm m}$, $\boldsymbol{k}_{\rm i}$, and $\boldsymbol{k}_{\rm g}$ are the mode vector, the projection of the vector of the incident wave on the grating and the grating vector, respectively; and φ is the angle between the vectors $\boldsymbol{k}_{\rm i}$ and $\boldsymbol{k}_{\rm g}$.

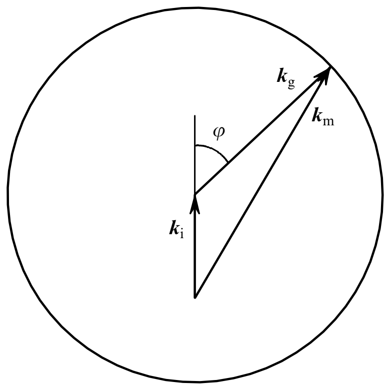

Figure 1. Matching diagram for the wave vectors upon excitation of a WGM; $\boldsymbol{k}_{\rm m}$, $\boldsymbol{k}_{\rm i}$, and $\boldsymbol{k}_{\rm g}$ are the mode vector, the projection of the vector of a incident wave on the grating and the grating vector, respectively.

By solving this equation for the wavelength of the excited mode, we obtain

$$\lambda = \Lambda\left[-\sin\theta\cos\varphi + \left(n^{*2} - \sin^2\theta\sin^2\varphi\right)^{1/2}\right]. \quad (2)$$

Here, θ is the angle of radiation incidence on the grating; n^* is the effective refractive index of the excited waveguide

B N Zvonkov, K E Zinov'ev, D H Nurligareev, I F Salakhutdinov, V V Svetikov, V A Sychugov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 117769 Moscow, Russia

Received 24 August 2000
Kvantovaya Elektronika **31** (1) 35 – 38 (2001)
Translated by A V Uskov

mode; and Λ is the corrugation period of the grating. Eqn (2) relates the wavelength of the excited mode, the angle of incidence and the angle between the grating grooves and the plane of incidence. Thus, by placing a selective mirror with a given corrugation period inside a cavity, one can provide the resonance condition for a given radiation wavelength by changing the angle of incidence and the angle between the grating grooves and the plane of incidence.

We used in our studies a semiconductor laser with an aperture of 360 μm, the maximum of the emission spectrum at a wavelength of 1000.2 nm ($T = 27$°C), and the FWHM of the emission spectrum of 30 nm. One of the LD faces had the reflectivity of 100 %, and the other one had an antireflection coating to minimise its influence on lasing. The emission spectrum of a laser with an external 12 %-mirror had the FWHM of 2.5 nm for the current exceeding the threshold current by 30 % ($J = 1.3J_{th}$), and the FWHM increased to 3.6 nm for the current $J = 1.5J_{th}$.

The parameters of the laser diode radiation were studied in a three-mirror cavity. The cavity in which the collinear interaction of TM-polarised radiation with a WGM occurs is shown schematically in Fig. 2. A focusing lens was placed inside the cavity to collimate the radiation incident on the grating. This allowed us to decrease the generation threshold due to an increase in the reflectivity from the WGM and a decrease in the intracavity losses.

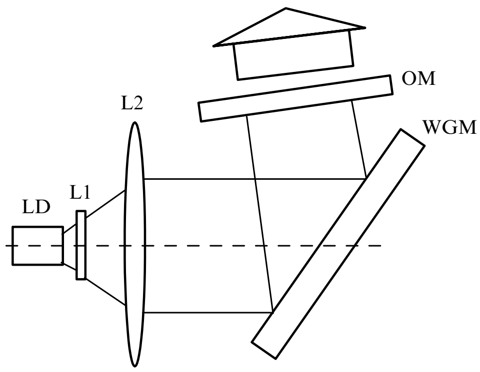

Figure 2. Scheme of the cavity with collinear interaction of the TM-polarised radiation with the WGM: (LD) laser diode; (L1) cylindrical lens; (L2) focusing lens; (WGM) waveguide – grating mirror; (OM) 12-% output mirror. The $p - n$-junction plane lies in the figure plane.

In accordance with the orientation of the grating grooves relative to the plane of incidence, we used two types of the intracavity interaction of light with the grating: collinear ($\varphi = 0$) and noncollinear ($\varphi = 90°$). The waveguide-grating mirrors were fabricated by the holographic method with subsequent ion etching. The Ta_2O_5 layer ($n = 2.05$) deposited on a glass substrate ($n = 1.512$ at $\lambda = 1$ μm) was used as a waveguide. The thickness of the waveguide layer, the grating period, and the corrugation depth were calculated for each case separately.

2. Cavity with collinear incidence of radiation on a WGM

In a cavity with collinear incidence of radiation on the grating of a waveguide mirror, the mirror was calculated so that the waveguide mode was excited by TM-polarised radiation in the minus first diffraction order at the angle of incidence, corresponding to the Brewster angle. In this case, the specular reflection from the WGM is formed only due to the radiative losses of the waveguide mode. Thus, the WGM plays simultaneously the role of a narrow-band selective filter and of an element which provides an increase in the area of the reflected flux of the single mode radiation, which is necessary to suppress the transverse modulation of laser radiation.

The calculations performed for this case gave the following parameters of the waveguide layer: the layer thickness $h = 270$ nm, the corrugation period $\Lambda = 411$ nm, and the corrugation depth $2\sigma = 200$ nm. The calculated decay coefficient α_{rad} of the mode with the wavelength $\lambda = 998$ nm was 140 cm^{-1}. Therefore, the product $d\alpha_{rad}$ (where d is the size of the radiation spot on the waveguide surface, $d \approx 0.3$ mm in our case), which is known as the criterion of anomalous reflection [4], is equal to 4.2 for our cavity geometry. Thus, the condition $d\alpha_{rad} > 1$ for the observation of anomalous reflection was fulfilled. The experimental curve of anomalous reflection for the fabricated mirror with the above parameters and for emission with a wavelength of 998 nm is shown in Fig. 3.

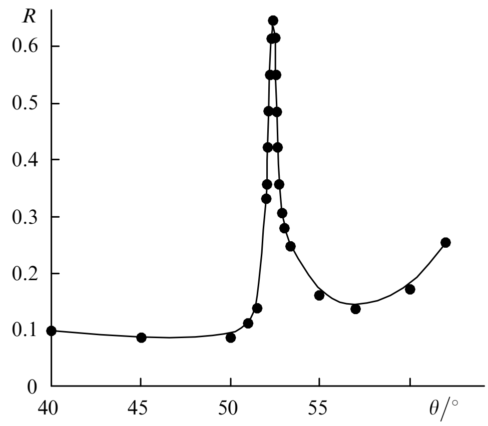

Figure 3. Dependence of the reflectivity of the TM-polarised radiation on the angle of incidence on the WGM in the collinear regime (the wavelength is 998 nm, the corrugation period of the grating is $\Lambda = 411$ nm).

The study of emission of a semiconductor laser in such a cavity showed that the use of a WGM inside the cavity allows one to obtain stable lasing in the wavelength range from 994 to 1013 nm (Fig. 4) with the FWHM of the laser line of 0.1 nm (Fig. 5). The dependence of the wavelength on the angle of incidence calculated from Eqn (2) is in good agreement with the experimental data. We used in calculations the experimentally measured value $n^* = 1.684$. The difference between the slopes of the curves is explained by the fact that the luminescence spectrum for the given laser diode has bell-like shape with a maximum at 1002 nm. The reflection spectrum of the WGM has the same shape, but its width is smaller. Thus, the maximum of the reflection spectrum and, hence, the laser wavelength are shifted to the luminescence maximum of the laser diode.

Measurements of the lasing spectra at different pump currents showed that the width of the lasing spectrum measured at the $0.1I_{out}$ level (I_{out} is the intensity of the fundamental mode) increases with increasing current due to the appearance of additional transverse modes. The output

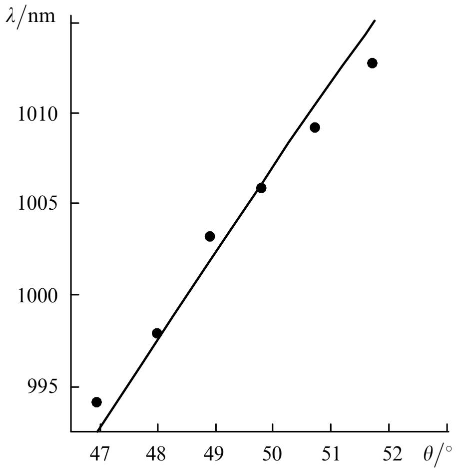

Figure 4. Dependence of the radiation wavelength of a LD on the angle of incidence in a cavity with collinear incidence of light on the WGM (the experimental data are shown by points, the solid curve is calculated from Eqn (2)).

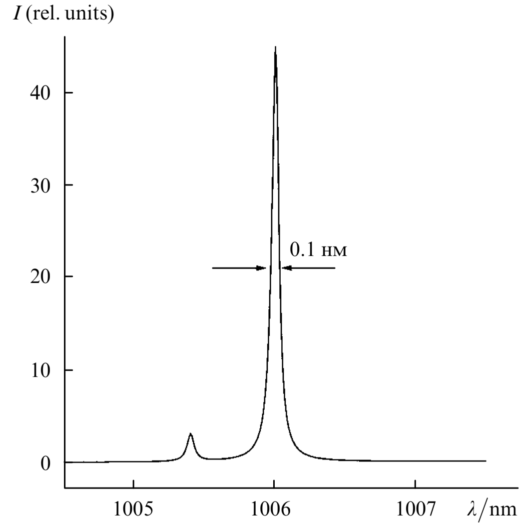

Figure 5. Output spectrum of a LD with a cavity with collinear incidence of the TM-polarised radiation on the WGM.

laser power increases monotonically with increasing pump current up to $1.5J_{\text{th}}$. In this case, the divergence of radiation in the plane of the $p-n$-junction virtually does not change and is equal to $0.15°$. This is explained by the fact that the output spectrum is sufficiently narrow over the entire range of pump currents studied, and even in the case of the filamentation, the filtering properties of the intracavity waveguide mirror provide the narrow-band output radiation.

3. Cavity with noncollinear incidence of radiation on a WGM

The scheme of a cavity with noncollinear incidence of radiation on a WGM is as a whole analogous to the scheme with collinear incidence of radiation with the TM-polarisation (Fig. 2). We changed only the orientation of grooves relative to the plane of incidence and the orientation of the grating plane in such a way that they would correspond to the condition of noncollinear incidence of radiation with TE-polarisation on the WGM. We studied the interaction of the TE-polarised radiation with the WGM because the waveguide mode of this type is characterised by lower dissipative losses.

Fig. 6 shows the angular distributions of the anomalous reflectivities of radiation with TE- and TM-polarisations from the fabricated WGM with the thickness $h = 182$ nm, the corrugation period $\Lambda = 642$ nm, and the corrugation depth $2\sigma = 206$ nm. One can see that TM-polarised radiation can excite TM and TE modes in the waveguide grating [4], whereas the incident TE-polarised radiation can excite only the TE-mode in the grating. As expected, the total losses upon excitation of the waveguide by the TM-radiation proved to be larger than those upon excitation by the TE-radiation.

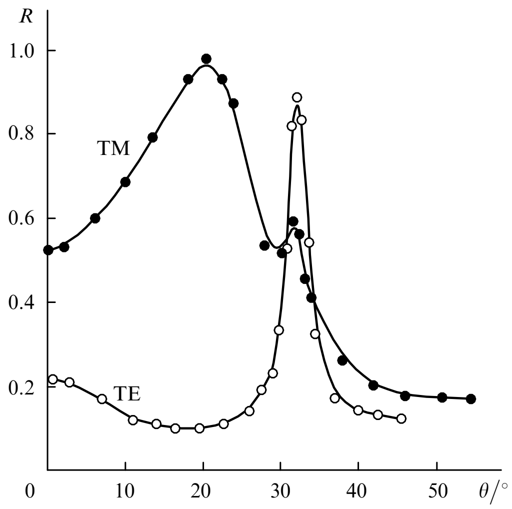

Figure 6. Dependencies of the reflectivity of with TE- and TM-polarised radiation on the angle of incidence on the WGM in the noncollinear regime (the wavelength is 998 nm, the corrugation period is $\Lambda = 642$ nm).

As in the case of collinear incidence, a focusing lens was placed inside the cavity to decrease the divergence, and hence, to increase the reflectivity from the WGM.

Experiments showed that this scheme of cavity allows one to obtain stable lasing in the wavelength range from 997 to 1005 nm with the laser line FWHM from 0.7 to 1.2 nm. Fig. 7 shows the experimental dependence of the laser wavelength on the angle of radiation incidence on the WGM, and also the curve calculated from Eqn (2). We used in calculations the experimentally measured value of the effective refractive index of the waveguide mode $n^* = 1.656$, and the angle φ between the grating vector and the projection of the plane of radiation incidence on the grating was chosen to be $89.8°$. One can see that the experimental data and calculations are in good agreement. The deviation of the angle φ from $90°$ is within the accuracy of the angle setting. The difference between the slopes of the curves is the same as that for the cavity with collinear incidence of light on the grating.

Studies of the output power and the lasing spectrum at different pump currents showed that the output power increases monotonically up to the current $J = 1.8J_{\text{th}}$ (Fig. 8), the power being equal approximately to the power of the laser without the WGM. For $J \leqslant 1.3J_{\text{th}}$, the lasing spectrum consisted of three narrow peaks of width no larger than 0.15 nm and located equidistantly with the total FWHM no larger than 0.7 nm. For $J = 1.8J_{\text{th}}$, the spectrum broadened

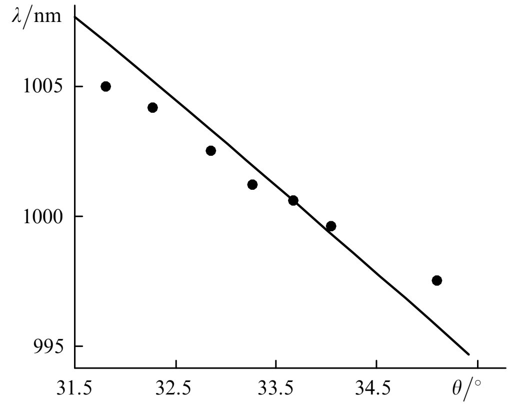

Figure 7. Dependence of the laser wavelength on the angle of incidence for a cavity with noncollinear incidence of light on the WGM (the experimental data are shown by points; the solid curve is calculated from Eq. (2) for $n^* = 1.656$ and $\varphi = 89.8°$).

to 1.2 nm due to the appearance of parasitic longitudinal modes caused by the reflection from the output face of the semiconductor laser (Fig. 9). The divergence of radiation in the $p-n$-junction plane was 0.15° for pump currents studied.

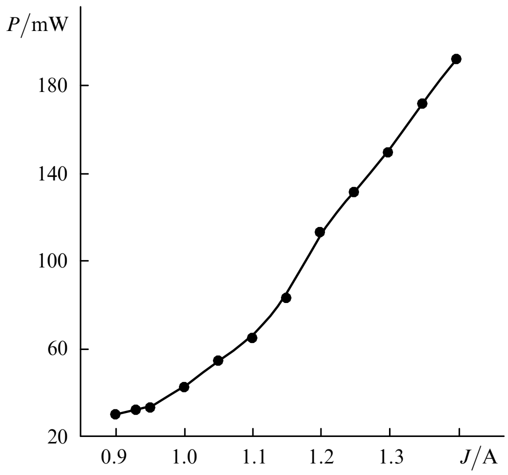

Figure 8. Dependence of the laser output power on the laser pump current for a cavity with noncollinear incidence of light on the WGM.

Therefore, an external cavity with oblique incidence of radiation on the WGM allows one to narrow to 0.1 nm the output spectrum of a wide-aperture semiconductor laser and tune the laser wavelength within the luminescence line of the laser diode.

Acknowledgements. The work was supported by the Russian Foundation for Basic Research (Grants Nos 99-02-82500 and 00-02-17442), as well as by the programm 'Integratsiya' (Grant No. A0103/99).

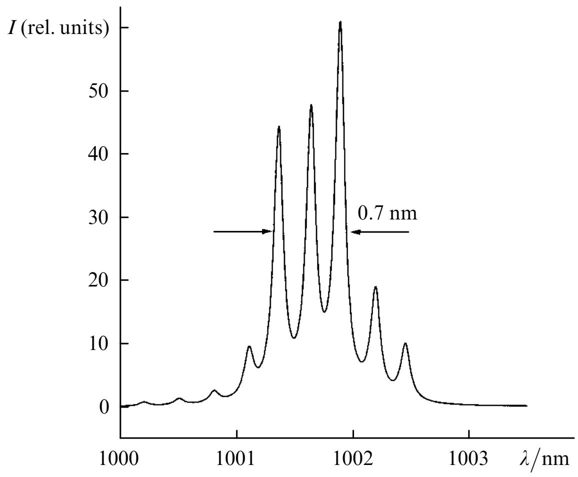

Figure 9. Output spectrum of a LD in a cavity with noncollinear incidence of the TE-polarised radiation on the grating.

References

1. Parke R et al. *IEEE Photon. Technol. Lett.* **5** 297 (1993)
2. Guel-Sandoval S et al. *Appl. Phys. Lett.* **66** 2048 (1995)
3. Demidov D M et al. *Kvantovaya Elektron.* **25** 789 (1998) [*Quantum Electronics* **28** 768 (1998)]
4. Trudy IOFAN **34** (1991)
5. Golubenko G A, Svakhin A S, Sychugov V A, Titschenko A V *Kvantovaya Elektron.* **12** 1334 (1985) [*Sov. J. Quantum Electron.* **15** 886 (1985)]
6. Kondratyuk V A, Mikhailov V A, Lyndin N M, Sychugov V A, Par'e O *Kvantovaya Elektron.* **26** 175 (1999) [*Quantum Electronics* **29** 175 (1999)]