Quantum Electronics **40** (10) 851 – 854 (2010)

©2010 Kvantovaya Elektronika and Turpion Ltd

PACS numbers: 42.55.Px; 42.60.Da; 42.81.Pa
DOI: 10.1070/QE2010v040n10ABEH014379

A semiconductor ring laser: study of its characteristics as a rotation sensor

V.V. Akparov, V.G. Dmitriev, V.P. Duraev, A.A. Kazakov

***Abstract*. A semiconductor ring laser (SRL) with a radiation wavelength of 1540 nm and a fibre ring cavity is developed and studied in several main lasing regimes. An SRL design based on a semiconductor optical travelling-wave amplifier and a ring cavity, composed of a single-mode polarisation-maintaining fibre, is considered. The SRL is studied in the regime of a rotation speed sensor, in which the frequency shift of counterpropagating waves in the SRL is proportional to its rotation speed. The minimum rotation speed that can be detected using the SRL under consideration depends on the cavity length; in our experiment it turned to be 1 deg s^{-1}. The changes in the threshold current, emission spectrum, and fundamental radiation wavelength upon closing and opening the SRL ring cavity and with a change in its radius are also investigated.**

Keywords: *semiconductor ring laser, semiconductor optical amplifier, Sagnac effect, laser rotation sensor, ring cavity.*

1. Introduction

Semiconductor ring lasers (SRLs) have an external (generally, fibre) ring cavity [1, 2]. They are complex nonlinear self-oscillating systems with distributed parameters, in which many different lasing regimes can be excited (unidirectional and bidirectional regimes, frequency beat regime of counterpropagating waves, self-modulation regime, dynamic chaos regime, etc. [3 – 9]).

SRLs are of great interest because they may exhibit more (in comparison with the conventional semiconductor laser diodes) optical phenomena, have a larger number of lasing regimes, and provide wider possibilities of controlling radiation by relatively simple methods (location of various control elements in the external ring cavity). The use of low-loss fibre cavities makes it possible to design ring lasers with superlong cavities, which are of both fundamental and practical importance. SRLs can be applied in optical communication lines, as elements of various devices for optical data processing, in navigation and control systems as sensors of angular parameters of motion, in high-frequency and microwave oscillators (as master oscillators) [10 – 26], and in many other devices.

SRLs with a fibre cavity are designed based on the active element of a travelling-wave amplifier with a wedge-shaped active channel and transparent cavity faces [25, 26]. Light is injected and extracted using single-mode optical fibres.

The purpose of this study was to develop an SRL with a radiation wavelength $\lambda = 1540$ nm and a fibre ring cavity and analyse its characteristics in some main lasing regimes, including its operation as a rotation speed sensor.

2. Experimental

The SRL design is shown in Fig. 1. The laser consists of a cermet housing of the 14-pin DIL type ('Butterfly') (*1*); an active element (*2*); a microcooler (*3*); a thermistor (*4*); and a single-mode optical polarisation-maintaining fibre (*5*), closed into a ring and connected with the SRL active element. Cylindrical microlenses (*6*) are formed at the fibre ends, which are connected with the active element. An X-shaped optical coupler (*7*) is placed in the ring cavity [using connectors (*8*) and a socket (*9*)] to measure the light parameters.

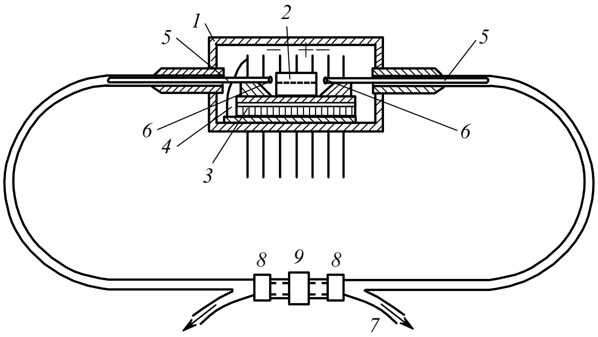

Figure 1. SRL design elements (clarifications in text).

To improve the pump efficiency and the optical confinement factor, reduce the temperature dependence and radiation spectral width, and increase the fraction of laser radiation injected into the single-mode optical fibre, we used an InGaAsP/InP heteroepitaxial structure with five quantum wells (Fig. 2). The composition of the In$_x$Ga$_{1-x}$As structure corresponded to lasing at $\lambda = 1540$ nm. The

---

V.V. Akparov 'Nolatech' Joint Stock Company, ul. Vvedenskogo 3, 117342 Moscow, Russia;
V.G. Dmitriev, V.P. Duraev, A.A. Kazakov Federal State Unitary Enterprise, M.F. Stelmakh 'Polyus' Research and Development Institute, ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: nolatech@mail.ru

Received 18 June 2010
Kvantovaya Elektronika **40** (10) 851 – 854 (2010)
Translated by Yu.P. Sin'kov

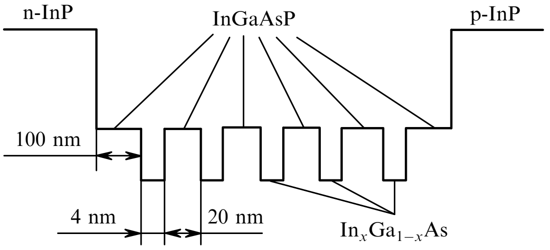

Figure 2. Geometry of a quantum-size InGaAsP/InP structure with a lasing wavelength $\lambda = 1540$ nm.

barrier layers of InGaAsP quaternary solid solution corresponded to $\lambda = 1250$ nm. The SRL active element had a ridge-like design (Fig. 3) and was 1600 μm long; the mesastripe width was 3 μm. The mesastripe was formed by photolithography so as to make an angle of 7° with the transparent faces of the active element.

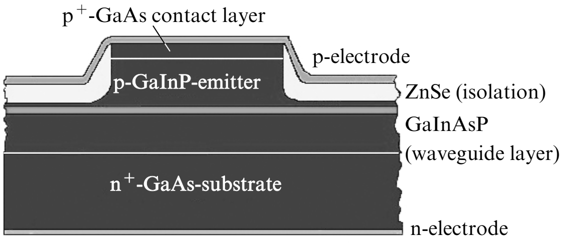

Figure 3. Cross section of a ridge-like active element.

The active-element temperature was maintained constant with an error of 0.01 °C using a microcooler. The cylindrical lenses at the fibre ends provided a 70 % efficiency of radiation coupling into the fibre. The X-shaped optical coupler provided 50 % radiation extraction from the ring cavity.

3. Experimental study of SRL

The watt–ampere characteristics of an SRL with a wavelength of 1540 nm, measured before and after closing the ring cavity, are shown in Fig. 4. The superluminescent radiation power, i.e., before closing the ring (the regime of a travelling-wave amplifier), was 1.9 mW at a pump current of 250 mA. In the closed-ring regime the SRL threshold current was 70 mA and the power in the lasing regime at a pump current of 140 mA amounted to 12 mW.

Figure 5 shows the SRL emission spectra measured with an ANDA optical spectrum analyser before and after ring closing. The superluminescent emission spectrum of the travelling-wave amplifier (before ring closing) had a half-width of 30 nm at $\lambda = 1536.4$ nm, whereas the SRL emission spectrum had a half-width of 0.1 nm at $\lambda = 1540.2$ nm. Thus, the radiation wavelength increases from 1536.4 nm (in the superluminescent radiation regime) to 1540.2 nm (in the lasing regime), and the spectrum in the lasing regime sharply narrows.

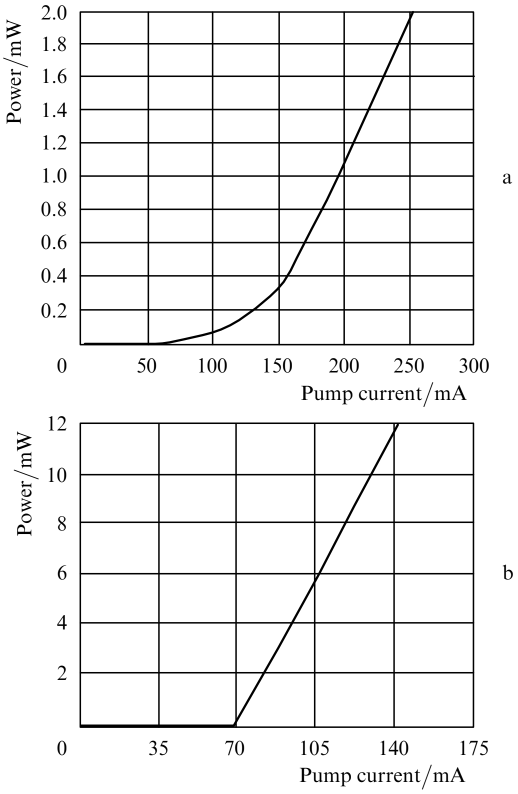

Figure 4. SRL watt–ampere characteristics (a) before and (b) after closing the ring cavity.

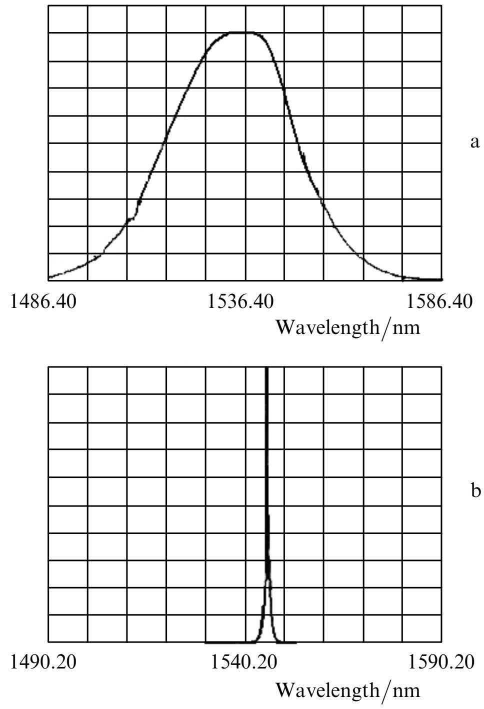

Figure 5. Optical radiation spectra of (a) semiconductor optical amplifier and (b) SRL.

We tried to experimentally detect the effect of nonreciprocity on the SRL lasing parameters. The ring laser cavity is known to be sensitive to nonreciprocity, because the Sagnac effect causes splitting of the frequencies of counterpropagating waves in the absence of locking, and the difference of these frequencies is proportional to nonreciprocity [4]. The latter can be introduced into the ring cavity in a very simple way: by rotating the ring contour around the sensitivity axis. To this end, the SRL was mounted on a rotating table to be rotated at a speed from 1 to 100 rpm. The change in the Sagnac beating frequency, Δf, was determined from the formula

$$\Delta f = \frac{2R\Omega}{n\lambda},$$

where R is the ring radius, Ω is the table rotation speed, and n is the refractive index of the medium.

A schematic of the experimental setup for measuring the SRL response to rotation around the sensitivity axis, oriented perpendicularly to the laser cavity plane, is shown in Fig. 6. The SRL cavity had a diameter of 11 cm and contained a 800-m-long single-mode optical fibre coil.

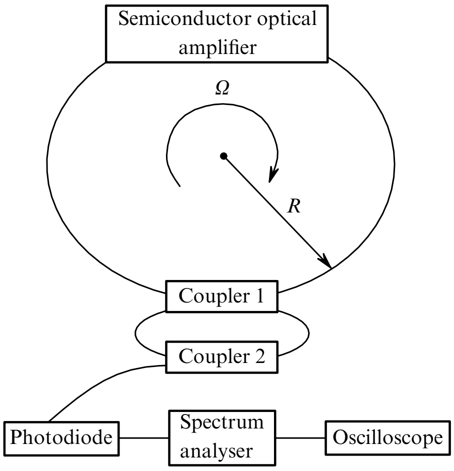

Figure 6. Schematic of the experimental setup for measuring the SRL response to rotation.

A directional coupler was used to extract some part of radiation of the counterpropagating wave from the cavity. Two counterpropagating waves interferred in the coupler 2 and arrived at the photodetector. The photodetector signal was applied to an RF spectrum analyser. All fibre components were made of a polarisation-maintaining fibre and connected by FC/APC connectors.

Figure 7 shows the RF spectral signal from the photodetector measuring the radiation of an immobile SRL (for which the optical frequencies of counterpropagating waves coincide). The photodetector has a quadratic nonlinearity and selects the beat spectrum for many optical modes falling in the RF range. The frequency interval between the optical modes, $\Delta f = c(Ln)^{-1}$, is 250 kHz at the SRL cavity length $L = 800$ m. The spectrum contains equidistant lines, with spacing equal to the intermodal gap; the linewidth is less than 3 kHz.

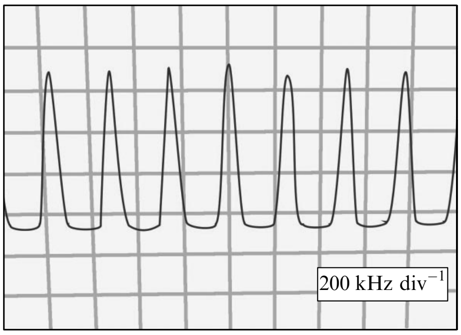

Figure 7. RF beat spectrum of ring-laser optical modes.

When nonreciprocity exists (for example, upon SRL rotation), the optical frequencies should be split in the absence of frequency locking. Obviously, due to the fairly strong scattering in the SRL active element, one would expect counterpropagating waves to be locked in a wide frequency range. Indeed, in our experiment this range was found to be approximately 1 deg s^{-1}. At some SRL rotation speed one can leave the locking range and find splitting of counterpropagating wave frequencies.

The RF beat spectrum for counterpropagating waves upon SRL rotation beyond the locking range with a speed of ~ 5 deg s^{-1} is shown in Fig. 8. This spectrum contains three frequency components (one central and two lateral). The central component exactly corresponds to the intermodal beat frequency of two neighboring optical modes when the SRL is immobile. However, upon SRL rotation, each mode is split into two optical components (we will refer to them as 'bottom' and 'top'), spaced by an interval equal to the Sagnac beat frequency. In this case, the central frequency in the RF spectrum retains its position and is equal to the difference in the optical frequencies of the 'bottom' (or 'top') components of two neighboring split modes. The low-frequency (left) RF component in Fig. 8 corresponds to the difference in the frequencies of the 'top' optical component of the lower frequency optical mode and the 'bottom' optical component of the higher frequency mode. Accordingly, the higher frequency (right) RF spectral component in Fig. 8 corresponds to the difference in the frequencies of the 'bottom' optical component of the lower frequency optical mode and the 'top' component of the higher frequency mode. Obviously, the distance between the neighbouring RF components exactly coincides with the Sagnac beat frequency, which is proportional to the SRL rotation speed.

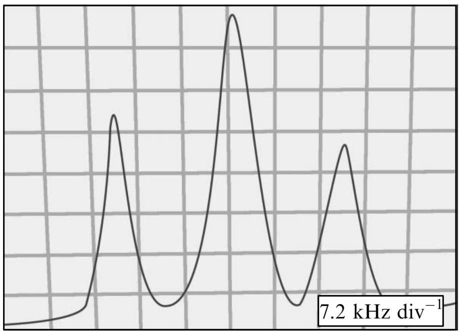

Figure 8. RF beat spectrum of split counterpropagating waves at an SRL rotation speed of ~ 5 deg s^{-1}.

Figure 9 presents the dependence of the Sagnac beat frequency on the SRL rotation speed. This dependence is linear, with a proportionality (scale) factor of 900 Hz deg^{-1} s. It was established that the minimum rotation speed that can be experimentally detected with an SRL decreases with increasing cavity length. In particular, at a cavity length of 800 m we could measure a rotation speed of 1 deg s^{-1}.

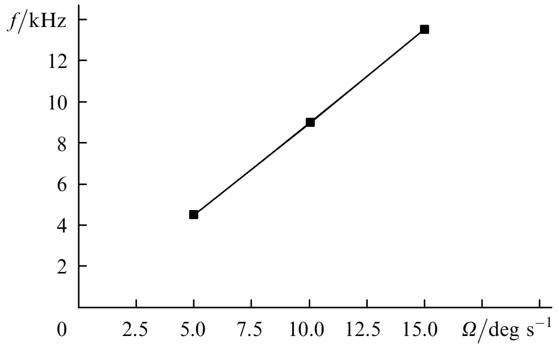

Figure 9. Dependence of the beat frequency of split counterpropagating waves on the SRL rotation speed.

4. Conclusions

An SRL with a radiation wavelength of 1540 nm and a fibre ring cavity was developed and investigated in several main lasing regimes. We considered the SRL design based on a semiconductor optical travelling-wave amplifier and a ring cavity, consisting of a single-mode polarisation-maintaining fibre. The changes in the threshold current and the radiation wavelength and spectrum were investigated upon closing and opening the SRL ring cavity and as functions of the cavity radius.

The SRL operation as a rotation speed sensor was investigated by measuring the RF beat spectrum of counterpropagating waves. The frequency shift of counterpropagating waves in the SRL was found to be proportional to its rotation speed. The minimum rotation speed that could be detected with the SRL under consideration depends on the cavity length; in our experiment it was 1 deg s^{-1}. The scale factor is 900 Hz deg^{-1} s.

The results of this study are preliminary, and the investigation of the SRL parameters, including the regime with nonreciprocity formed in the cavity, will be continued.

References

1. Bogatov A.P., Eliseev P.G., Okhotnikov O.G. *Pis'ma Zh. Tekh. Fiz.*, **8** (13), 799 (1982).
2. Bogatov A.P., Eliseev P.G., Okhotnikov O.G. *Pis'ma Zh. Tekh. Fiz.*, **10** (7), 397 (1984).
3. Takahashi Y., Sekiya S., Iwai N. *Opt. Rev.*, **10** (4), 315 (2003).
4. Kravtsov N.V., Lariontsev E.G. *Kvantovaya Elektron.*, **21**, 903 (1994) [*Quantum Electron.*, **24**, 883 (1994)].
5. Show W.W., Gea-Banacioche J., et al. *Rev. Mod. Phys.*, **57** (1), 61 (1985).
6. Kravtsov N.V., Kravtsov N.N. *Kvantovaya Elektron.*, **27**, 98 (1999) [*Quantum Electron.*, **29**, 378 (1999)].
7. Basov N.G., Krokhin O.N., Popov Yu.M. *Usp. Fiz. Nauk*, **72** (2), 161 (1960).
8. Duraev V.P., Nedelin E.T., Nedobyvailo T.P., Sumarokov M.A. *Foton-Ekspress*, (6), 20 (2005).
9. Akparov V.V., Duraev V.P., Logginov A.S., Nedelin E.T. *Vestn. Mosk. Univ., Ser. 3: Fiz., Astron.*, (3), 45 (2006).
10. Vu Van Lyk, Duraev V.P., Eliseev P.G., et al. Preprint FIAN No. 47 (Moscow, 1989).
11. Dmitriev V.G., Duraev V.P., Kazakov A.A., Nedelin E.T. *Fotonika*, (4), 18 (2008).
12. Duraev V.P., Kazakov A.A., Medvedev S.V. *Fotonika*, (1), 16 (2010).
13. Duraev V.P., Dmitriev V.G., Kazakov A.A. *Obozrenie Prikl. Promyshl. Mat.*, **16** (4), 647 (2009).
14. Donati S., Giuliani G., Sorel M. *Alta Frequenza – Rivista di Elettronica*, **9** (6), 61 (1997).
15. Sunada S., Tamura S., Inagaki K., Harayama T. *Phys. Rev. A*, **78**, 053822 (2008).
16. Tamura S., Inagaki K., Noto H., Harayama T. *Proc. SPIE Int. Soc. Opt. Eng.*, **6770**, 677014 (2007).
17. Taguchi K., Fukushima K., Ishitani A., Ikeda M. *Opt. Quantum Electron.*, **31**, 1219 (1999).
18. Ishida T., Tamura S., et al. *Proc. SPIE Int. Soc. Opt. Eng.*, **7004**, 700450 (2008).
19. Yao X.S., Maleki L. *Opt. Lett.*, **22** (24), 1867 (1997).
20. Yao X.S., Maleki L. *Opt. Lett.*, **21** (7), 483 (1996).
21. Ikeda M., Taguchi K. *Proc. Conf. CLEO/Europe* (Glasgow, Scottland, UK, 1998) p. CWE2.
22. Taguchi K., Fukushima K., Ishitani A., Ikeda M. *IEICE Trans. Electron.*, **E82-C** (4), 659 (1999).
23. Duraev V.P., Nedelin E.T., Nedobyvailo T.P., Sumarokov M.A. RF Patent No. 41924 (2004).
24. Duraev V.P. *Lightwave*, (2), 45 (2004).
25. Duraev V.P. *Lightwave*, (4), 56 (2005).
26. Golikova E.G., Duraev V.P., Kozikov S.A., Krigel' V.G., Labutin O.A., Shveikin V.P. *Kvantovaya Elektron.*, **22**, 105 (1995) [*Quantum Electron.*, **25**, 85 (1995)].