

PACS numbers: 42.55.Px; 42.60.Lh
DOI: 10.1070/QE2013v043n11ABEH015248

Dedicated to the memory of Prof. L.A. Rivlin

Broadband semiconductor optical amplifiers of the spectral range 750 – 1100 nm

E.V. Andreeva, S.N. Il'chenko, M.A. Ladugin, A.A. Lobintsov, A.A. Marmalyuk, M.V. Shramenko, S.D. Yakubovich

Abstract. **A line of travelling-wave semiconductor optical amplifiers (SOAs) based on heterostructures used for production of broadband superluminescent diodes is developed. The pure small-signal gains of the developed SOA modules are about 25 dB, while the gain bandwidths at a level of –10 dB reach 50 – 100 nm. As a whole, the SOA modules cover the IR spectral range from 750 to 1100 nm. The SOAs demonstrate a high reliability at a single-mode fibre-coupled cw output power up to 50 mW. Examples of application of two of the developed SOA modules as active elements of broadband fast-tunable lasers are presented.**

Keywords: *semiconductor optical amplifier, tunable and single-frequency lasers.*

1. Introduction

The physical characteristics of semiconductor optical amplifiers (SOAs) are well studied and published in hundreds of papers. Among the pioneering studies of single-pass (travelling-wave) SOAs , we should note a series of works supervised by L.A. Rivlin [1]. At present, SOAs have found application in many engineering fields, first of all in fibre-optic communication systems. In these systems, SOAs are used not only for amplification of optical signals, but also as modulators, logical switches, commutators, routers, and nonlinear converters [2]. Today, 50% of the worldwide laser market in monetary terms accrues to semiconductor lasers, 31% of this amount belonging to telecommunication systems [3]. There are no data on the relative amounts of SOAs and laser diodes (LDs), but SOAs obviously compose a large fraction of this market.

A lot of SOAs modules for these applications, including broadband amplifiers with an optical gain bandwidth exceeding 100 nm, are produced commercially. All the above refers to the spectral range 1200 – 1700 nm. Local fibre-optic communication systems with visible and near IR LDs are also being rapidly developed, but they almost do not use SOAs.

E.V. Andreeva, S.N. Il'chenko, A.A. Lobintsov, M.V. Shramenko Superlum Diodes Ltd., post box 70, 117454 Moscow, Russia; e-mail: andreeva@superlumdiodes.com;
M.A. Ladugin Sigm Plyus Ltd, ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: maximladugin@mail.ru;
S.D. Yakubovich Moscow State Institute of Radio Engineering, Electronics, and Automation (Technical University), prosp. Vernadskogo 78, 119454 Moscow, Russia; e-mail: yakubovich@superlumdiodes.ru;
A.A. Marmalyuk OJSC 'M.F. Stel'makh Polyus Research Institute', ul. Vvedenskogo 3, 117342 Moscow, Russia; e-mail: marm@siplus.ru

Received 30 May 2013; revision received 31 July 2013
Kvantovaya Elektronika **43** (11) 994 – 998 (2013)
Translated by M.N Basieva

Most often, SOAs of these regions are used as output power amplifiers of various laser systems and as active elements of single-frequency and tunable lasers with selective external cavities [4]. For example, Sacher Lasertechnik (Germany) produces tens of models of tunable semiconductor lasers with classical Littman and Littrow external cavities, as well as LDs with antireflection coated faces as active elements. The overall tuning range of these lasers is 630 – 1740 nm. The tuning bandwidths of individual near-IR lasers are about 20, 30, 40, and 50 nm in the ranges 750–800, 800–900, 900–1000, and 1000 – 1100 nm, respectively.

As is known, the use of semiconductor quantum-well heterostructures (nanoheterostructures) makes it possible to obtain optical gain bandwidths of about 100 nm in the mentioned spectral regions [5]. However, until recently, the gain bandwidths of available SOAs operating in these regions did not exceed 40 – 50 nm (see, for example, [6]). Broadband superluminescent diodes (SLDs) in these regions have spectral half-widths of about 50, 70, 95, and 110 nm, respectively [7 – 10]. To produce broadband travelling-wave SLDs based on quantum-well heterostructures, one must optimise the design of active elements. It is desirable to achieve the maximum optical gain bandwidth and simultaneously a sufficiently high single-pass gain, a moderate injection current, and a relatively weak superluminescence, which in this case is the parasitic background.

In this work, we develop and study six types of SOA modules, whose gain bands in sum completely cover the spectral range 750 – 1100 nm. We also describe broadband fast-tunable lasers, in which two of the new SOA modules are used as active elements.

2. Experimental samples and their characteristics

The configuration of the active channel of the studied SOAs does not differ from the traditional design used in SLDs [9]. This channel has a form of a straight ridge waveguide about 4 μm wide with an inclination of 7° with respect to the crystal faces, which had two-layer antireflection coatings with an effective reflection coefficient of $\sim 10^{-4}$. The above-mentioned optimisation consisted in the growth and post-growth processing of new heterostructures with required optical properties, in fabrication of experimental SOAs from them, in study of these SOAs, and in the selection of the optimal active channel length L_a. The travelling-wave SOAs differ from light emitting SLD modules by a more complex design and a more complicated assembly technology. The main difference consists in the use of two rather than of one units of precision coupling with the input and output single-mode fibres (SMFs). The SOA crystals were mounted on special heat-

Table 1. Main technical characteristics of the studied SOAs. Structures I–IV have one quantum well, structures V and VI have two quantum wells.

Structure type	Active layer composition and thickness	Active channel length/μm	Gain bands at the 10 dB level/nm	Maximum gain/dB	Maximum output power/mW
I	$Al_{0.1}Ga_{0.9}As$ (1×10.0 nm)	1100	755–825	26	25
II	GaAs (1×9.0 nm)	1200	795–875	25	50
III	$In_{0.02}Ga_{0.98}As$ (1×11.0 nm)	1200	825–915	27	30
IV	$In_{0.2}Ga_{0.8}As$ (1×6.0 nm)	1200	885–990	28	30
V	$In_{0.3}Ga_{0.7}As$ (2×5.5 nm)	1000	955–1080	25	20
VI	$In_{0.35}Ga_{0.65}As$ (2×7.0 nm)	1200	1010–1110	24	20

sinks, which provided convenient approach of the SMF microlenses to the active channel faces. The module was packaged in a Butterfly housing containing Peltier microcoolers and thermistors for thermal stabilisation of SOAs.

In this work, we performed technological investigations in order to find the optimal combination of solder alloys with different melting temperatures for assembling the SOA module. Note that the complete module contains nine main contacts soldered using five different solder alloys with melting temperatures from 104 to 183 °C. As a result of these investigations, we developed a well reproducible assembly technology for production of reliable hermetic modules operable at environmental temperatures from –55 to +70 °C. The input and output SMFs were made of isotropic fibre or of PANDA fibre with a wavelength cutoff corresponding to the SOA gain band. If necessary, the ends of waveguides were supplied with FC/APC connectors. The characteristics of the SOA modules were studied at a stable temperature of 25 °C in continuous injection regime.

The method for measuring the main technical characteristics of SOA modules is described in detail in [7]. These measurements were done using two SOA modules of the same type, one of which served as an active element of the tunable laser generating the input signal. Figure 1 shows typical spectra of pure single-pass gain (fibre-to-fibre) of the developed SOAs measured at injection currents corresponding to the maximum spectral half-width. It should be noted that these currents are somewhat higher than the currents at which the spectral peaks are equalised in quantum-well SLDs based on the same heterostructures. Our experience shows that the gain $G \sim 10$ dB is sufficiently high for fulfilment of the threshold conditions for SOAs placed in an external cavity with reasonable dissipative and radiative losses. From this estimate, the effective gain bandwidths of the considered SOAs vary from 70 (type I) to 125 nm (type V).

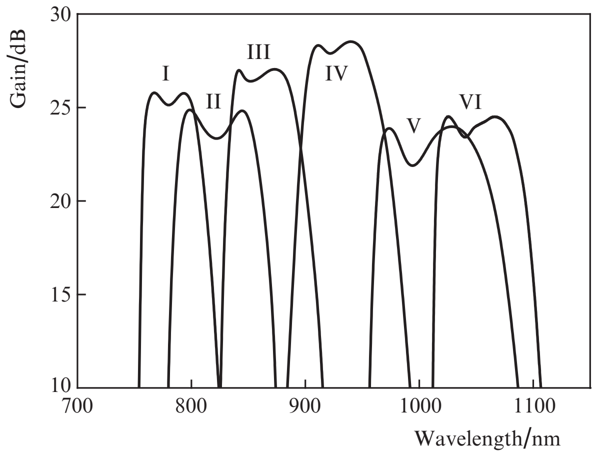

Figure 1. Small-signal gain spectra of new broadband near-IR SOAs of types I–VI.

The geometric parameters and chemical composition of the active layers of heterostructures of types I–VI are demonstrated in Table 1. The last column shows the output powers at the SMF exit at which preliminary lifetime tests of the SOA modules were performed. It should be noted that the free-space output power corresponding to the catastrophic optical damage threshold of these modules varies from 80 to 150 mW. Thus, at least some types of SOAs can have noticeably higher output powers (SMF coupling coefficient from 55 % to 70 %). The question of how this will reflect on the service lifetime requires additional investigations.

As an example, below we present the measured steady-state gain characteristics for the SOA of type II. The spectral width of a signal sent to the SOA through an optical isolator did not exceed 0.05 nm. Its power was varied in a wide range using a controllable fibre-optic attenuator. Figure 2 shows the gain spectrum evolution in a linear regime at the input signal power below –15 dBm. At low injection currents, a sufficiently high gain is observed only in the spectral band corresponding to the quantum transitions from the ground state. As the pump level increases, the quantum transitions from the excited subbands also contribute to the output radiation.

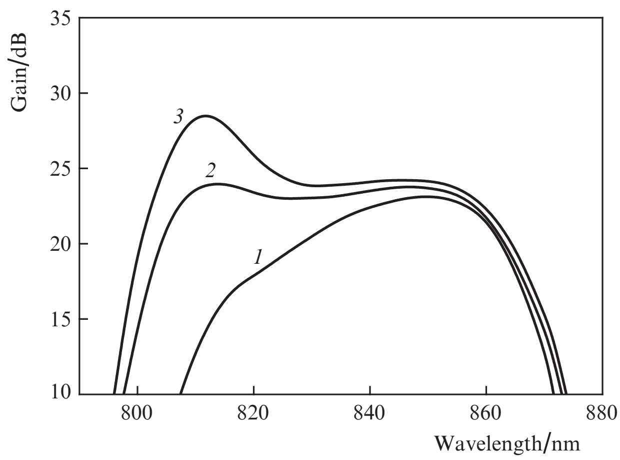

Figure 2. Small signal gain spectra of a SOA (type II) at the injection currents I_{SOA} = (*1*) 100, (*2*) 150, and (*3*) 200 mA.

Figure 3 presents the dependences of the SOA output power and gain on the input signal power at wavelengths of 805, 830, and 860 nm, which correspond to the edges and the centre of the gain band. The output power in the regime of the manual or automatic power control (APC) can be kept at a

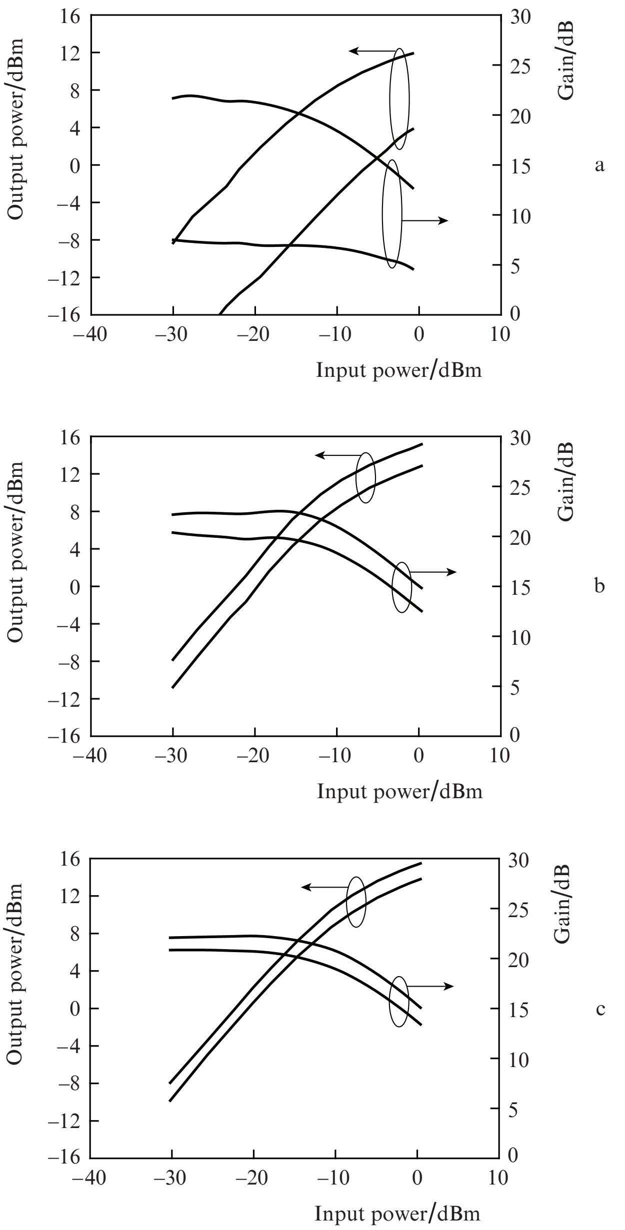

Figure 3. Transmission characteristics of a narrow-band input signal at a wavelength of (a) 805, (b) 830, (c) and 860 nm and I_{SOA} = 100 mA (lower curves) and 150 mA (upper curves) for a SOA of type II.

constant level by changing the SOA injection current. However, the excess (in dB) of the useful signal over the superluminescent pedestal (SMS) in this case changes. The corresponding output radiation spectra, as well as the dependences of the SOA injection current and SMS on the input signal wavelength are shown in Fig. 4. In the given case, the SOA operated in the gain saturation regime ($G \approx 14$ dB).

Figure 5 presents the chronograms of lifetime tests of three SOAs in a double-pass regime at an output power of 50 mW. The shown curves allow one to estimate that the lifetime is no shorter than 10 000 h. Similar investigations and tests were also performed for the other types of considered SOAs. This made it possible to begin production of six new SOA modules with conventional names SOA-332-785, SOA-352-830, SOA-352-870, SOA-472-930, SOA-522-1010, and SOA-542-1060. These amplifiers have considerably broader gain bandwidths than their analogues available on the optoelectronic market.

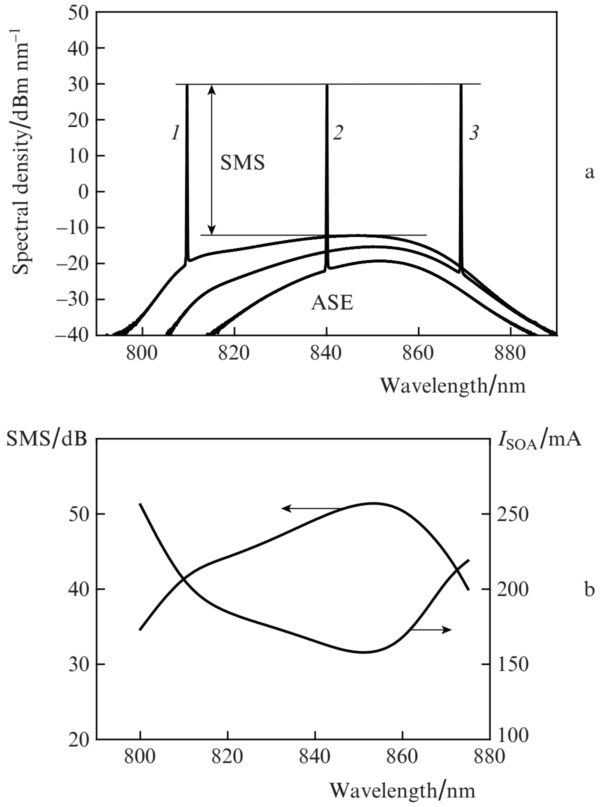

Figure 4. (a) Output spectra at the total optical output power of 50 mW (P_{in} = 2 mW) at wavelengths of (*1*) 810, (*2*) 840, and (*3*) 870 nm and (b) dependences of SMS and I_{SOA} on the input signal wavelength. ASE is amplified spontaneous emission of superluminescence.

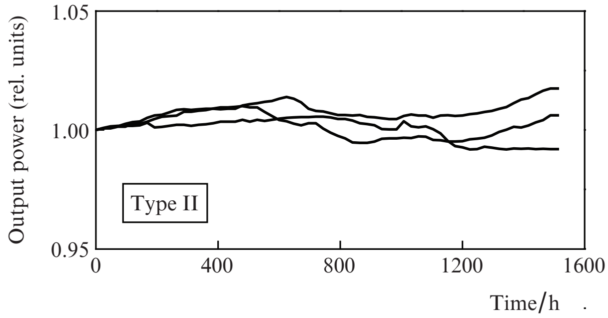

Figure 5. Chronograms of lifetime tests of SOAs at a cw output power of 50 mW.

3. Semiconductor laser continuously tunable within the spectral band 1010–1110 nm

Below we study an experimental sample of a tunable laser in which a SOA module of type IV plays the role of an active element. In the external cavity, a Corning PANDA-980 polarisation maintaining fibre was used. As a spectrally selective element, we used an acoustooptic tunable filter (AOTF) with quasi-collinear interaction of optical and acoustic waves, which is similar to the filter described in [11]. Although the AOTF has relatively large dimensions and a rather slow response, it has obvious advantages compared to the other selective elements of tunable lasers, namely, a high accuracy and a good reproducibility of the imposed wavelength, which is determined by the frequency of the RF master oscillator. In contrast to the schemes described in [11, 12], in this work we used a fibre-optic ring cavity, which contained an AOTF-coupled optical isolator responsible for unidirectional lasing. This scheme allows one to obtain a higher output power than the linear schemes in which the SOA operates in the double-pass regime. We studied two types of ring schemes (S1 and S2) differing by the position of the output fibre-optic splitter (Fig. 6). To optimise the scheme, we used PMTC-06 (AFR Ltd.) broadband splitters with coupling ratios of 50:50, 30:70, and 20:80. The optimal relation between the threshold current and the external efficiency was achieved for the second splitter. The splitter was located behind the AOTF in the first scheme and directly behind the SOA in scheme 2. The advantage of the first scheme consists in the pure spectrum of the output radiation (SMS > 55 dB). The second scheme allows one to achieve a higher output power, but the spectrum in this case contains a superluminescent pedestal, whose height changes with laser tuning. Note that SMS at a level of 30 – 40 dB is acceptable for many practical applications. In particular, the tunable lasers based on LDs with antireflection-coated faces, which were mentioned in the Introduction, also are not free of this drawback. In addition, these lasers are characterised by mode-hop tuning, while the considered schemes demonstrate continuous tuning within the entire gain band of SOAs.

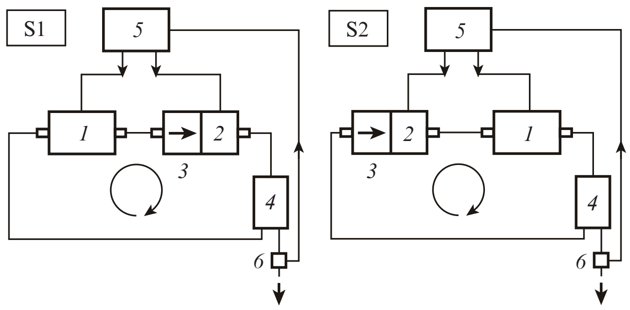

Figure 6. Schemes of tunable lasers with an external fibre-optic ring cavity:
(*1*) SOA module of type II; (*2*) AOTF; (*3*) optical isolator; (*4*) 30:70 fibre-optic splitter; (*5*) controller; (*6*) monitor photodiode of the APC system.

Figure 7 shows the light – current characteristics of lasers of both types when the AOTF is tuned to a wavelength of 1064 nm. Note that scheme S2 yields a 2.5-fold higher external efficiency. The tuning curves of lasers in the APC regime at different output powers are shown in Fig. 8. The injection current was limited by 200 mA, at which the SOA module passed the lifetime test. As was expected, the spectral tuning range increases with decreasing output power. Figure 9 presents typical output spectra of the lasers. For the lasers in the S1 scheme, the relative noise level did not exceed –55 dB and was lower than the sensitivity of the used ADVANTEST-Q8347 spectrometer. For the lasers in the S2 scheme, the SMS varied from 30 to 50 dB depending of the spectral tuning and output power (Fig. 10). A controller of the SOA and AOTF allowed manual tuning with an accuracy of 0.05 nm or a linear wavelength sweeping in the given range with a rate up to 10^4 nm s^{-1}. The instantaneous linewidth did not exceed 0.1 nm. Our investigations allowed us to improve considerably the previously

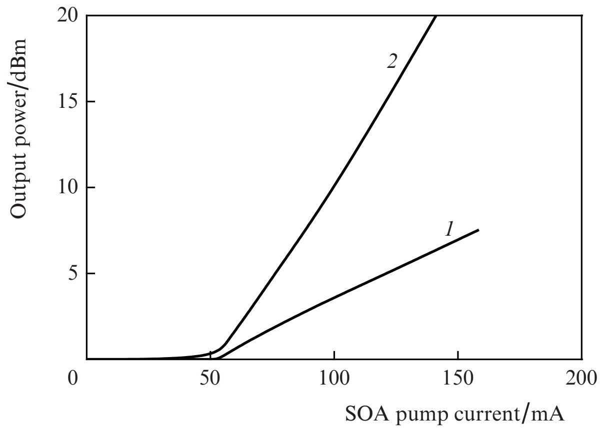

Figure 7. Light – current characteristics at a wavelength of 1060 nm for lasers in schemes (*1*) S1 and (*2*) S2.

produced tunable laser BroadSweeper-1060-01, which used a less efficient SOA and a linear external cavity scheme.

The authors of [13] described a fast-tunable laser based on a SOA of type V, which operated in a double-pass regime in an external cavity containing a diffraction grating and a rotating ten-sided mirror prism. Wavelength tuning was achieved within a range of 121.5 nm centred at 1020 nm with an average output power of 8.2 mW, a sweeping frequency of 18 kHz, and an instantaneous linewidth of 0.085 nm. The use of this laser as a light source in an ophthalmic optical coherence tomography system made it possible to obtain images of eye retina and cornea with a resolution of 2.9 μm.

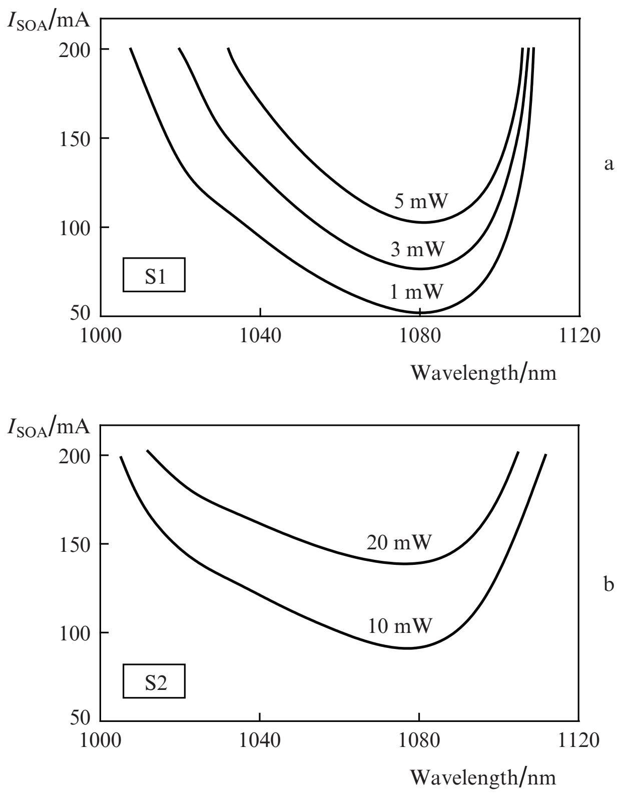

Figure 8. Tuning curves for different output powers of lasers in schemes S1 and S2 (APC regime, SOA of type VI).

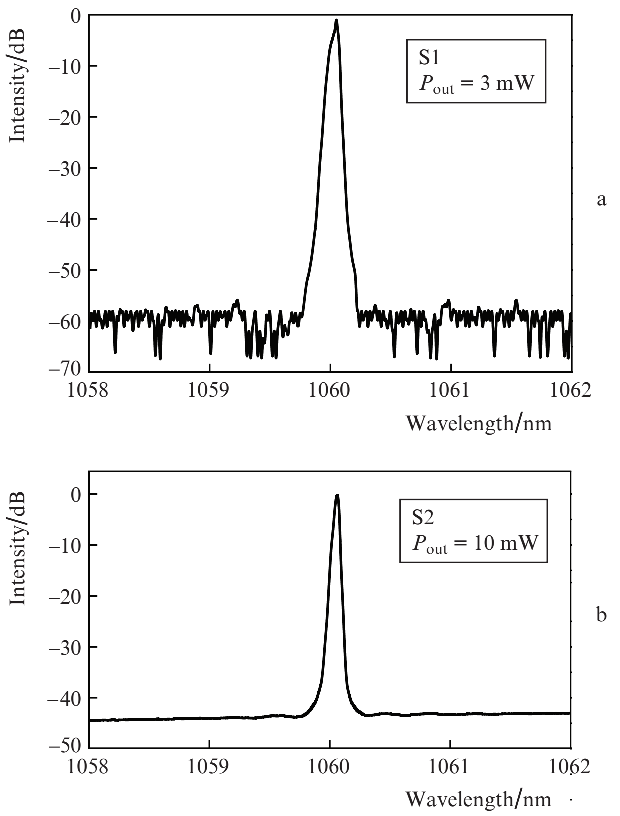

Figure 9. Output spectra of lasers in schemes S1 and S2 in the case of tuning to a wavelength of 1060 nm.

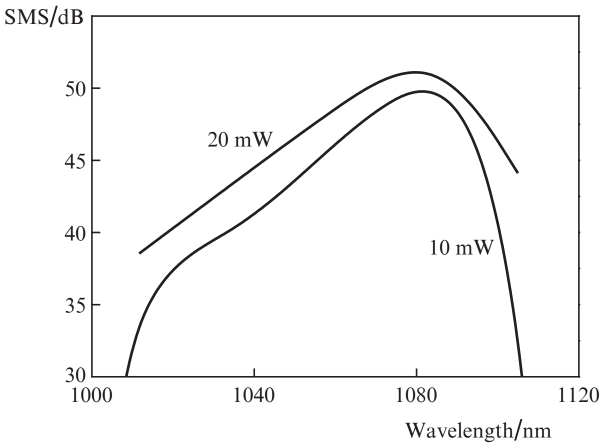

Figure 10. Wavelength dependence of SMS at different output powers of the laser in scheme S2.

4. Conclusions

Six new models of travelling wave SOA modules, which have no industrial analogues, are developed based on heterostructures with AlGaAs, GaAs, and InGaAs quantum-well active layers with optical gain bands about 100 nm wide. As a whole, the gain bands of the modules cover the IR range 750–1100 nm. It is shown that these SOAs can be efficiently used as active elements of tunable lasers.

Acknowledgements. The authors are grateful to A.T. Semenov for initiating the reported studies and helpful discussions and to L.N. Magdich for supplying an improved AOTF sample. This work was partially supported by the Federal Targeted Program 'Scientists and Science Educators of Innovative Russia' (Grant No. 14.V37.21b0756).

References

1. Rivlin L.A., Semenov A.T., Yakubovich S.D. *Dinamika i spektry izlucheniya poluprovodnikovykh lazerov* (Dynamics and Spectra of Semiconductor Lasers) (Moscow: Radio i svyaz', 1983).
2. Connelly M.J. *Semiconductor Optical Amplifiers* (Dordrecht: Kluwer Acad. Publ., 2002).
3. Overton G., Nogee A., Belforte D.A., Holton C. *Laser Focus World*, **49** (1), 36 (2013).
4. Buus J., Amann M.C., Blumental D. *Tunable Laser Diodes and Related Optical Sources* (Hoboken: Wiley, 2005).
5. Helstein M.M., Mehuys B., Yariv A. *Appl. Phys.*, **54** (11), 1092 (1989).
6. Duraev V.P., Medvedev S.V. *Nauch. Priborostr.*, **22** (3), 53 (2012).
7. Il'chenko S.N., Kostin Yu.O., Kukushkin I.A., Ladugin M.A., Lapin P.I., Lobintsov A.A., Marmalyuk A.A., Yakubovich S.D. *Kvantovaya Elektron.*, **41** (8), 677 (2011) [*Quantum Electron.*, **41** (8), 677 (2011)].
8. Kostin Yu., Lapin P., Shidlovski V., Yakubovich S. *Proc. SPIE Int. Soc. Opt. Eng.*, **7139**, 713905-1 (2008).
9. Mamedov D.S., Prokhorov V.V., Yakubovich S.D. *Kvantovaya Elektron.*, **33** (6), 471 (2003) [*Quantum Electron.*, **33** (6), 471 (2003)].
10. Lapin P.I., Mamedov D.S., Marmalyuk A.A., Padalitsa A.A., Yakubovich S.D. *Kvantovaya Elektron.*, **36** (4), 315 (2006) [*Quantum Electron.*, **36** (4), 315 (2006)].
11. Andreeva E.V., Magdich L.N., Mamedov D.S., Ruenkov A.A., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **36** (4), 324 (2006) [*Quantum Electron.*, **36** (4), 324 (2006)].
12. Lobintsov A.A., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **38** (7), 661 (2008) [*Quantum Electron.*, **38** (7), 661 (2008)].
13. Sang-Won Lee, Hyun-Woo Song, Moon-Youn Jung, Seung-Hwan Kim. *Opt. Express*, **19** (22), 21227 (2011).