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Highly efficient semiconductor optical amplifier for the 820 – 860-nm spectral range

A.A. Lobintsov, M.B. Uspenskii, V.A. Shishkin, M.V. Shramenko, S.D. Yakubovich

***Abstract*. A single-pass optical amplifier with a gain up to 32 dB at a wavelength of 840 nm is developed. Its high reliability is demonstrated at a single-mode fibre-coupled cw output power up to 50 mW. Examples of efficient application of this amplifier in MOPA systems are presented.**

Keywords: *semiconductor optical amplifier, MOPA system.*

1. Introduction

Investigations of semiconductor optical amplifiers (SOAs) began in the middle of the 60s of the last century in the USSR and USA soon after the advent of laser diodes (LDs) [1, 2]. SOAs differ from LDs by a strong suppression of optical feedback, which allows one to achieve a much higher single-pass gain. The first studied SOAs were travelling-wave SOAs based on GaAs laser homostructures with the gain maximum near 850 nm, which can operate only at cryogenic temperatures. Then, (GaAl)As/GaAs laser heterostructures were developed and used as a base for SOAs, which were able to operate at room and higher temperatures. A major contribution to these investigations was made by the groups of L.A. Rivlin and P.G. Eliseev (only in Quantum Electronics, they published more than ten papers). Later, as LDs have been created based on new semiconductor materials and structures (bulk heterostructures, layered quantum-well heterostructures, quantum wires, quantum dots) [3], corresponding SOAs were also developed and studied.

The SOAs of the 1250 – 1650-nm spectral range [4] found the widest application in fibre-optic communication systems. At present, dozens of models of these devices are available at the optoelectronic market. At the same time, the radiation of the near IR region (800 – 900 nm) is used only in local networks, where SOAs are not needed. SOAs of this region are frequently used as active elements in lasers with external (bulk or waveguide) cavities or as output boosters for low-power laser systems. The maximum output powers (several watts in the cw regime) are achieved in SOAs with wide and, as rule, ridge active channels, which were extensively studied in early 1990s (see, for example, [5]). The beam of these SAOs has almost diffraction-limited divergence and can be, in principle, with the use of a rather complicated optics, coupled into fibre waveguides, including single-mode fibres (SMFs) [6]. Usually, these SOAs are used in bulk optical schemes. Examples of such devices are TA chips (CoS) from TOPTICA PHOTONICS.

The market of traditionally constructed SOA modules with single-mode active channels and input/output SMFs for the considered spectral range is rather poor. As an example, we can mention QSOA-840 from QPHOTONICS LLC, as well as SOA-372 and SOA-382 from Superlum Diodes Ltd. These modules have the maximum SMF-to-SMF gain of 20 – 25 dB, the gain bandwidth of 15 – 40 nm, and the output power saturation level of the order of 10 mW. These values are noticeably lower than the record-high characteristics achieved for such SOAs in laboratory experiments. This occurs because, in contrast to LDs, the highly efficient SOAs, as well as the high-power superluminescent diodes (SLDs), operate under conditions of extremely high concentrations of nonequilibrium carriers, which makes it very difficult to achieve a satisfactory reliability, especially for devices based on heterostructures in the (GaAl)As system. In the present work, this technical problem is solved owing to the advanced technological methods of production of SOA active elements.

2. Experimental samples

The active elements of the studied SOAs had the traditional design. Their straight active channel was a single-mode ridge waveguide 4.0 μm wide and 1600 μm long. Its axis was tilted by 7° with respect to the normal to the crystal facets with dielectric antireflection coatings.

The active elements were produced using a (GaAl)As/GaAs single-layer quantum-well heterostructure grown by MOCVD epitaxy in an AIXTRON reactor. Compared to the SIGMOS-130 growth setup used by Superlum Diodes Ltd. for production of most of SLDs and SOAs, the AIXTRON reactor allows one to grow layers with better homogeneity and more perfect heterointerfaces.

Another technique used to form ridge waveguides was the inductively coupled plasma etching with an average ion energy of 150 eV. This method introduces much less defects

A.A. Lobintsov, M.V. Shramenko Superlum Diodes Ltd., P.B. 70, 117454 Moscow, Russia; e-mail: shramenko@superlumdiodes.com;
M.B. Uspenskii, V.A. Shishkin M.F. Stel'makh 'Polyus' Research and Development Institute (State Enterprise), ul. Vvedenskogo 3, 117342 Moscow, Russia
S.D. Yakubovich Moscow State Institute of Radio Engineering, Electronics and Automatics (Technical University), prosp. Vernadskogo 78, 117454 Moscow, Russia; e-mail: yakubovich@superlumdiodes.com

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in the near-surface region of the crystal than the previously used ion-chemical etching with an average ion energy of about 500 eV [7].

The advanced production technology of SLDs based on the bulk (GaAl)As/GaAs heterostructure (SLD-38 with the SMF-coupled output optical power up to 10 mW) allowed one to increase their service life to $(5-10)\times10^4$ h, which is proved by a large statistics. As will be shown below, this technology makes it possible to noticeably increase the reliability of quantum-well SLDs and SOAs operating with much higher output powers.

The SOA active elements were mounted on thermoelectric microcoolers in Butterfly housings with built-in thermistors. Using PILOT-4 controllers, the active element temperature was stabilised at a level of 25 °C at an operating current up to 450 mA and the environment temperature from −55 °C to +60 °C. As the input/output SMFs, we used Corning Pure Mode 780 isotropic fibres or Corning PANDA 850 polarisation-preserving fibres. In the coupling units, we used tilted end microlenses.

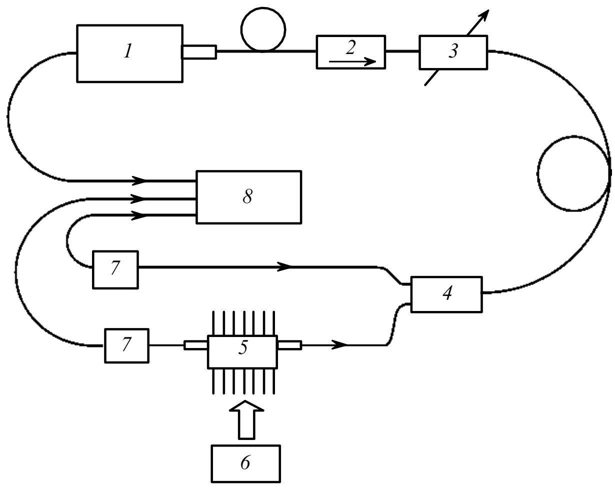

Figure 1. Measurement scheme: (*1*) BroadSweeper-840; (*2*) optical isolator; (*3*) tuneable optical attenuator; (*4*) fibre Y-coupler; (*5*) SOA module; (*6*) PILOT-4 controller; (*7*) optical power meters; (*8*) recording system.

3. Experimental results

To determine the maximum allowable output power, we measured the optical resistance of the SOA elements in the SLD regime. The threshold of their catastrophic optical degradation (COD) in the cw injection regime at 25 °C was 200 – 240 mW into the open space. Even this alone proves that the considered technological advances are rather promising. Note for comparison that SLDs of a similar design based on the same heterostructure produced by the traditional technology have the COD threshold of 100 – 150 mW. In subsequent investigations, we restricted ourselves by the SMF-coupled output power of 50 mW, which approximately corresponds to 100 mW into the open space. In the SLD regime, this output power from both active element facets was achieved at the injection current of 400 mA. From preliminary service-life tests in this regime, the average lifetime of the samples was estimated to be more than 7000 h.

The measurement scheme (Fig. 1) was similar to that described in [8]. The main difference was that as an input signal source we used a BroadSweeper-840 tunable laser with the following output characteristics [9]:

Tuning range/nm	825 – 875
Laser linewidth (FWHM)/nm	0.05
Output optical power/mW	
Low-power regime	1.0
High-power regime	3.0
Side-mode suppression (SMS) ratio/dB	> 50
Polarisation degree (%)	> 90

The laser allowed spectral tuning in the manual regime, in the regime of linear periodical sweeping with a rate up to 10^4 nm s^{-1}, and in the two-frequency regime (switching between two chosen wavelengths λ_1 and λ_2 with a given rate).

In this scheme, we studied a SOA module with a PANDA SMF. All the optical connections were made of the same fibre with the axes aligned upon welding. Optical isolator (*2*) (AC Photonics 850PM) attenuated the reflected signal in the above spectral band by more than 25 dB, which almost completely suppressed the parasitic optical feedback caused by reflection from the output laser mirror. With allowance for the losses in the cavity, attenuator (*3*), and welding points, the output power of SOA (*5*) could vary from fractions of microwatt to 1.0 mW. The optical gain was calculated by the formula

$$G = 10\,\mathrm{lg}\frac{P_{\mathrm{out}} - P_{\mathrm{out}}(P_{\mathrm{in}} = 0)}{P_{\mathrm{in}}}. \quad (1)$$

Figure 2 shows the small-signal ($P_{\mathrm{in}} = 1.0$ μW) optical gain spectra for different injection currents of the SOA. Unfortunately, due to the narrow wavelength tuning band of the laser ($\lambda_{\mathrm{min}} = 825$ nm), we failed to record the short-wavelength wing of the dependence $G(\lambda)$. The presented curves show that even at a moderate pumping (150 mA), the gain in the spectral maximum reaches 30 dB. With increasing the injection current, the gain increases and the spectral band of the $G(\lambda)$ profile broadens. At a current of 280 mA, this band is 25 nm wide at the −3 dB level and wider than 40 nm at the −10 dB level.

Figure 3 presents the transfer characteristics of the SOA at the same injection currents for the input signal at 845 nm

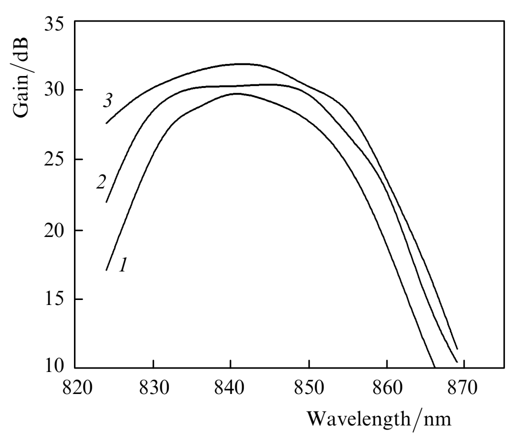

Figure 2. Small-signal optical gain spectrum for injection currents of 150 (*1*), 220 (*2*), and 280 mA (*3*).

(near the gain maximum). The curves are terminated at the points where the total output power (in the bands of the input signal and amplified spontaneous emission) reached 50 mW (17 dBm). The best spectral purity (high SMS) of the output signal is achieved at deep gain saturation and a corresponding decrease in the superluminescent 'pedestal'. The output emission spectra were recorded with an ANDO AQ6317B optical spectrum analyser, whose dynamic range exceeded 50 dB at the resolution of 0.01 nm and the above-mentioned level of the optical power. The SMS was determined as the excess of the narrow peak at the input signal wavelength over the superluminescent pedestal.

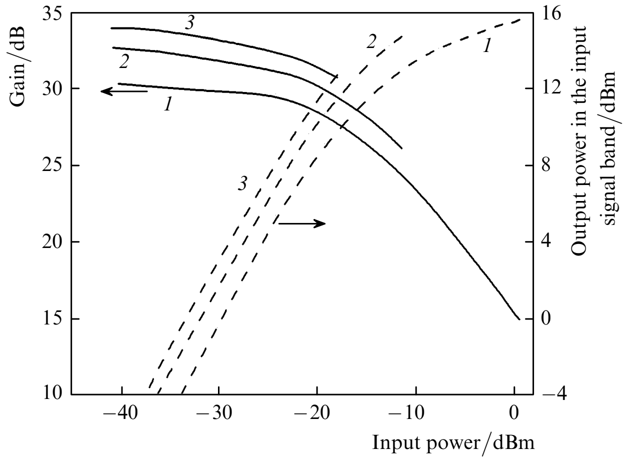

Figure 3. Transfer characteristics of the SOA at different powers of the 845-nm input signal and injection currents of 150 (*1*), 220 (*2*), and 280 mA (*3*).

Figure 4a presents the dependences of the SOA operating currents providing output powers of 25 and 50 mW on the input signal wavelength. To perform these measurements, we excluded attenuator (*3*) and Y-coupler (*4*) from the scheme. The signal from the output of optical isolator (*2*) (losses of about 1.5 dB) was directly sent to SOA input (*5*). The corresponding spectral dependences SMS(λ) are given in Fig. 4b. In the long-wavelength region of the tuning band ($\lambda > 860$ nm), this laser–amplifier system is not of practical interest. The high output power in this region is achieved due to a large contribution of superluminescence. At the same time, these dependences show that the SMS in the region 825–860 nm at the output power 50 mW exceeds 35 dB. This is smaller than the SMS of the laser itself, but is sufficiently high for many practical applications. Thus, the developed SOA module (preliminarily called SOA-382-HP) allows one to increase the output power of the BroadSweeper-840 tuneable laser by more than an order of magnitude retaining, in general, its unique spectral parameters.

SOAs in the gain saturation regime are in principle more reliable than SLDs of the same design emitting the same output power, because, at identical radiation loads on the output crystal facets, the former operate at a lower pump level and a smaller concentration of nonequilibrium carriers in the active layer. The result of preliminary service life tests of such MOPA systems are given below.

It is well known that high-power SLDs and SOAs are rather sensitive to the parasitic optical feedback. The MOPA system with an output SOA in the gain saturation regime is free of this drawback. Even a strong feedback can only slightly distort the output signal but cannot cause catastrophic optical degradation related to the breakdown of the SOA input facet.

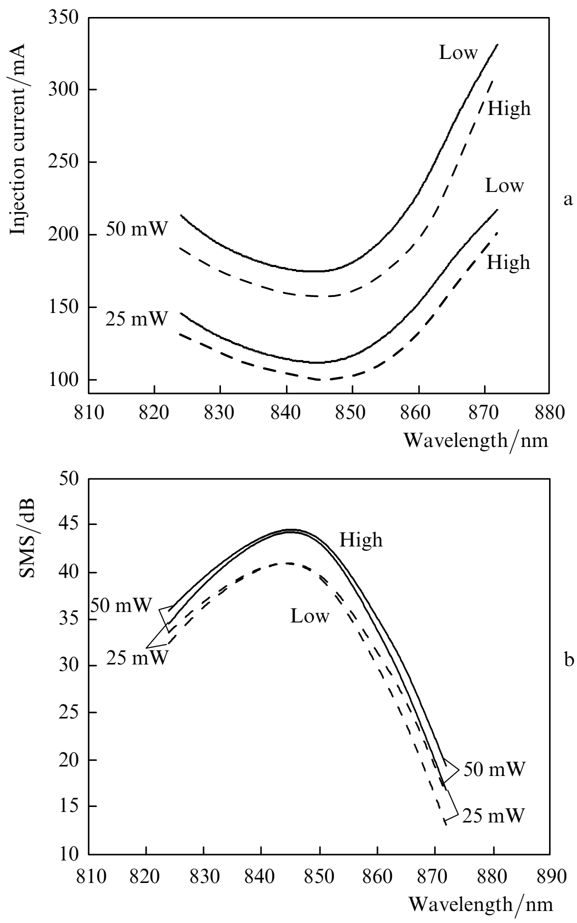

Figure 4. Wavelength dependences of the SOA injection currents corresponding to the output powers of 25 and 50 mW (a) and the corresponding SMS dependences (b) at $P_{\text{in}} \sim 0.7$ mW (Low) and ~ 2.0 mW (High).

4. Booster-840 optical power amplifier

Based on the developed SOA module, we fabricated a prototype of an optical power amplifier (preliminary name is Booster-840). Its appearance and scheme are shown in Fig. 5. The amplifier was assembled in a Schroff HF-Tubus standard housing and supplied from a dc source with a voltage of 9 V. We studied two amplifier modifications: based on an isotropic SMF and on a PANDA SMF. At the input and output of the scheme, we used FC/APC in-line connectors (*1*). In front of SOA (*5*), we placed optical isolator (*3*) and polarisation controller (*4*) (only in schemes with isotropic SMFs). A distinguishing feature of this device is that it contains an automatic power control (APC) system and a protection system, which blocks the SOA injection current in the absence of the input signal. The operation of these systems was controlled by modified PILOT-4M controller (*8*), which received signals from photodiode (*7*) [from fibre Y-coupler (*2*)] and monitor (*6*).

This device was initially developed as an amplifier for BroadSweeper-840 laser. The switch-off threshold of the

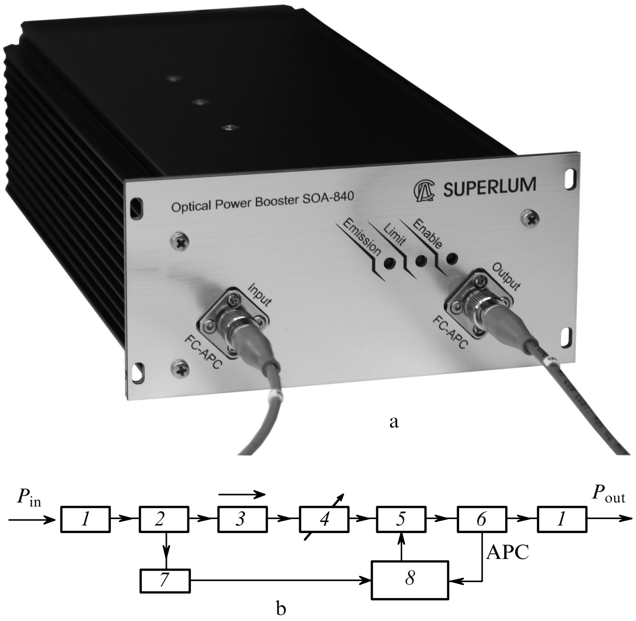

Figure 5. Appearance (a) and scheme (b) of a Booster-840 optical amplifier: (*1*) single-mode FC/APC optical connector; (*2*) fibre Y-coupler (95 : 5); (*3*) broadband fibre isolator; (*4*) polarisation controller (used in the case of isotropic SMFs); (*5*) SOA-382-HP; (*6*) OPM-1 fibre monitor (98 : 2); (*7*) photodiode; (*8*) PILOT-4M controller.

protection system was fixed at a level of 0.5 mW, while the APC system kept the output power at a level of 50 mW (these two values are controllable). The oscillograms shown in Fig. 6 illustrate the operation of this MOPA system in the regime of linear wavelength sweep within the band 825–860 nm with a frequency of 150 Hz, which corresponds to the spectral tuning rate of 6×10^3 nm s^{-1}.

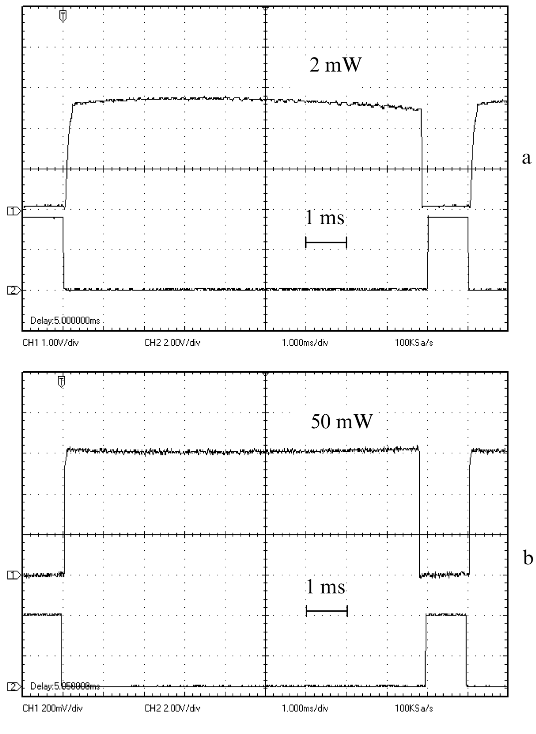

Figure 6. MOPA system consisting of a BroadSweeper-840 laser and a Booster-840 amplifier. Oscillograms of the input (a) and output (b) signals (sweep range 825–860 nm, sweep frequency 150 Hz, lower oscillograms belong to synchropulses).

Later, we studied a MOPA system with a low-power SLD module as a master oscillator and a Booster 840 prototype (with an isotropic SMF) as an output power amplifier. As a result, we created a source of a high-power (50 mW at the SMF output) and rather broadband (FWHM = 12 nm) radiation with the central wavelength at 850 nm. Investigations showed that these parameters very slightly depend on the SLD output characteristics, which is only required to have a sufficiently wide emission spectrum, which overlaps the SOA gain band, and an output power high enough to saturate the SOA (of the order of 1 mW). Figure 7 shows the SLD emission spectrum, the SOA superluminescence spectrum in the absence of the input signal with the switched-off protection system, and the output emission spectrum of the MOPA system in the APC regime. These output characteristics of the system are realised at a moderate (of about 165 mA) SOA injection current. It is appropriate to mention that the SMF-coupled output power of commercial superluminescent light sources of this spectral range does not exceed 30 mW.

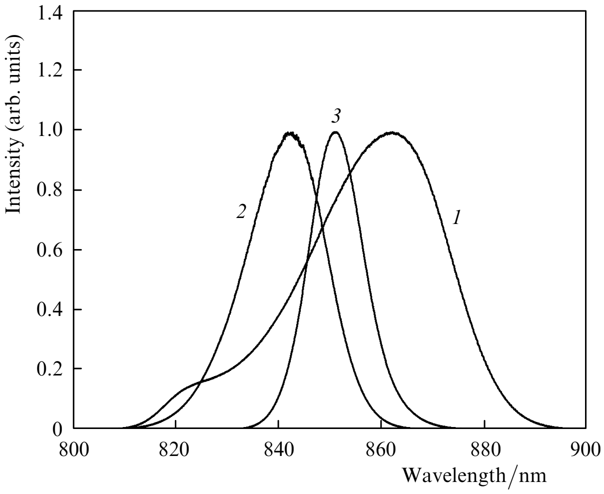

Figure 7. MOPA system consisting of an SLD-371 and a Booster-840. Emission spectra of the master SLD (*1*), of the SOA in the SLD regime (*2*), and of the MOPA system (*3*) at the SMF-coupled cw output power of 50 mW.

The above considerations about potentially high reliability and resistance to the parasitic feedback are also completely true for the considered MOPA system, whose lifetime was preliminarily tested in two stages. During the first 500 h, the APC system was switched off and the SOA operated at a stabilised injection current of 167 mA (the ACC regime). At the beginning of the test, the output power decreased with a rate of 0.5 % per day. Approximately after 300 h, this process slowed down (Fig. 8a). This behaviour is typical of most LDs and SLDs. For the next 500 h, the system operated in the APC regime with an SMF-coupled output power of 50 mW. In this case, the SOA injection current was observed to approximately linearly increase with a rate of about 0.1% per day (Fig. 8b). Recall that the active elements similar to the element used in the considered SOA demonstrated a rather high reliability in the SLD regime at the same output power. Their operating injection current was about 400 mA. According to the given data, the

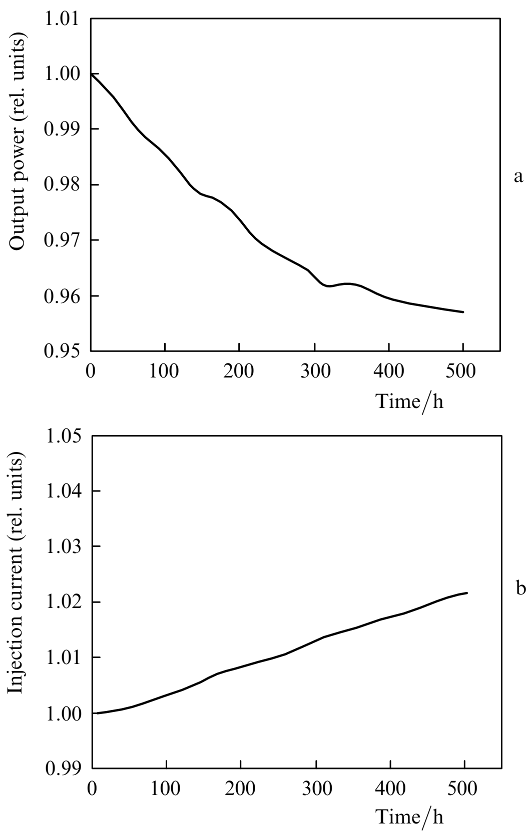

Figure 8. Chronograms of preliminary service life tests of the MOPA system in the ACC (a) and APC (b) regimes at the cw output power of 50 mW.

service life of the considered MOPA system is longer than 3×10^4 h. For practical applications that do not require so long service life (above three years of round-the-clock operation), this value, within reasonable limits, can be sacrificed to obtain a higher output power.

5. Conclusions

A prototype of a highly efficient SOA module is developed for the 820–860-nm spectral range. Its small-signal fibre-to-fibre gain can exceed 30 dB. The SOA was demonstrated to be highly reliable at an SMF-coupled cw output power up to 50 mW. Two types of MOPA systems, in which the developed SOA is used as an output power amplifier, have been studied.

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