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Tunable low-coherence light source with high spectral brightness

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Abstract. **Operation of a tunable tandem-type low-coherence light source with high spectral brightness based on commercially available optical elements (superluminescent diode, semiconductor optical amplifier, and bulk dwiffraction grating) is studied experimentally. A unique combination of the output source characteristics, namely, a spectral power density of 36 mW nm^{-1}, a wavelength tuning range of 35 nm (834–869 nm), and a more than 20-dB excess of the central peak intensity over the superluminescent pedestal, is experimentally obtained. It is shown that the output radiation spectrum with a width of 1.4 nm has a smooth bell-shaped profile with side lobes lying below the superluminescent pedestal. It is proved that such a light source is of practical interest for various applications.**

Keywords: *tunable light source, quantum-well heterostructure, superluminescent diode, semiconductor optical amplifier, diffraction grating.*

1. Introduction

Among a great variety of optical light sources available in the optoelectronics market, we should specially mention numerous devices designed using semiconductor superluminescent diodes (SLDs). These diodes have been rapidly developed owing to the progress in the growth technologies of heteroepitaxial structures and passed a long way from simple semiconductor devices with a spectral width not exceeding 20 nm and an optical power of a few milliwatts to high-power broadband semiconductor sources with unique output characteristics [1–3].

The use of a narrow transversely single-mode active channel with a width of several microns, which ensured the diffraction divergence at the exit of the semiconductor crystal (chip), made it possible to create a compact SLD module coupled with a single-mode fibre (SMF). At present, a wide range of such devices is extensively used in various scientific and practical applications requiring low-coherence light sources with high spectral brightness. The main applications include low-coherence interferometry, fibre-optic sensors of various types, gyroscopy, optical reflectometry, etc. [4, 5].

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Today, the market of commercial optical devices experiences an urgent demand for compact light sources with a relatively narrow radiation spectrum (1–2 nm) and a high spectral density (exceeding 10 mW nm^{-1}). Increased interest in devices of this type is expressed by companies that fabricate technological equipment for effective scribing of semiconductor wafers and crystals, perform genetic studies in biology and medicine, develop medical equipment for noncontact analysis of blood circulation in human body, and design devices for various laboratory applications (polarimeters, colorimeters, refractometers, etc.). It should be noted that, apart from high spectral power, these light sources should satisfy special requirements for the shape of the output optical spectrum, i.e., this shape must be smooth and, if possible, bell-like, have a low (below 15 dB) level of side lobes, and be independent of the output optical power and stable during the entire service life. An additional important condition is the possibility of tuning the peak wavelength of the output spectrum to the desired working wavelength.

In some cases, it is possible to use semiconductor lasers for these purposes [6], but they cannot completely satisfy the aforementioned requirements. In this situation, SLDs with high spectral brightness can be the optimal candidates for creating the required light source. A step in this direction can be the development of an SLD with a spectral width of 8 nm and a spectral power density of 12 mW nm^{-1} reported in [7]. Nevertheless, the development of a special narrow-spectrum SLD with required optical and power characteristics is a difficult and sometimes insoluble technical problem. One of the possible solutions of this problem can be the development of a light source with a tandem configuration based on a commercial SLD by separating part of master oscillator radiation with a spectral width of 1–2 nm by a spectrally selective element (for example, diffraction grating or spectral filter) and amplifying this radiation to a required power in a laser semiconductor optical amplifier (SOA) [8].

In the present work, we report the results of the development of an optical scheme of a tunable low-coherence light source with a high optical brightness using standard SLD, SOA, and bulk diffraction grating. All elements of the scheme are mass-produced and available in the market. We describe in detail the optical scheme and present the spectral, power, and tuning characteristics of the developed light source.

2. Optical scheme of the light source

Figure 1 shows the studied optical scheme of a tunable superluminescent source using a conventional tandem configuration of a master oscillator power amplifier (MOPA)

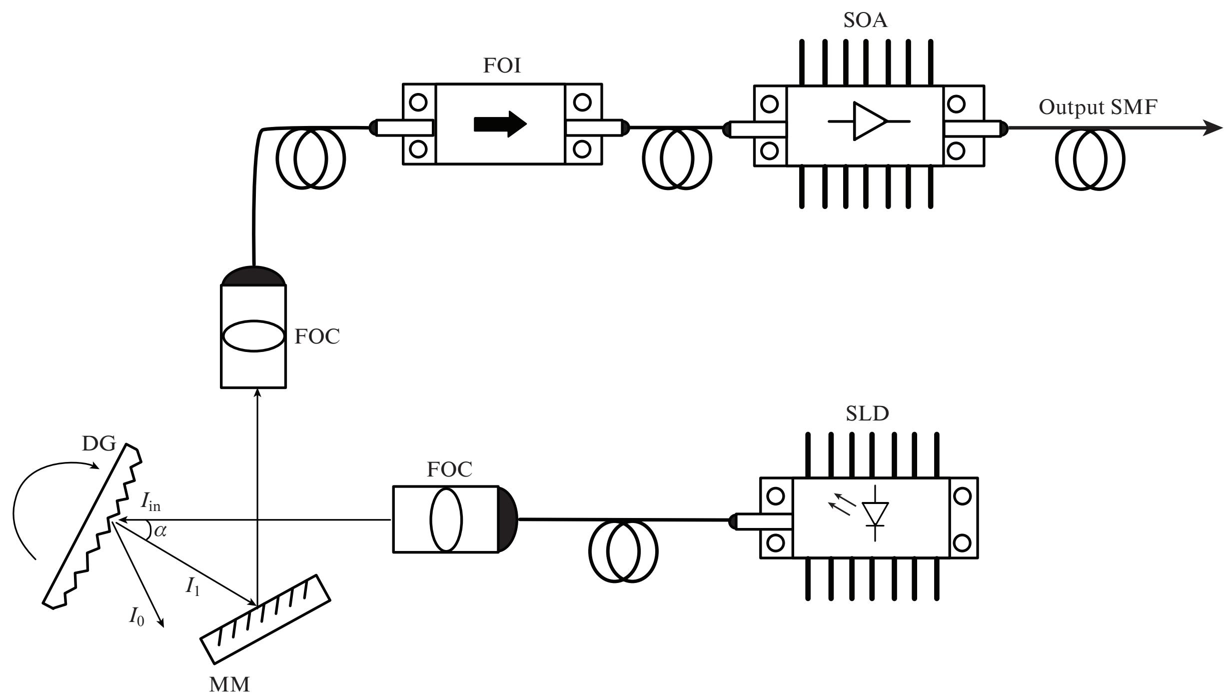

Figure 1. Optical scheme of a tunable superluminescent source:
(SLD) superluminescent diode; (FOC) fibre-optic collimator; (DG) diffraction grating; (MM) metal mirror; (FOI) fibre-optic isolator, (SOA) semiconductor optical amplifier; (I_{in}) incident light intensity; (I_1) and (I_0) light intensities in the first and zero diffraction orders, respectively. All optical fibres are polarisation-maintaining SMFs.

described in [9]. The scheme consists of two main cascades, i.e., a low-power master oscillator with spectral filtration and a high-power optical amplifier operating in the booster regime.

As a master oscillator, we used a commercial SLD-381 module (Superlum, Russia). As an active element, this module contained a semiconductor crystal based on a separate confinement double heterostructure (SCDH) in the (GaAl)As system with a bulk active layer 0.145 μm thick. The active element emitted superluminescence with a bell-shaped (quasi-Gaussian) profile and a peak at λ = 845 nm. The output optical power of the module was variable up to 30 mW with a slight variation in the spectral width in the range 13–15 nm (Fig. 2).

As a SOA module, we used a commercial SOA-372 amplifier (Superlum, Russia) based on a single-layer quantum-well heterostructure in the (GaAl)As system with an active layer 11 nm thick, which provided an optical gain exceeding 20 dB in the spectral range 820–870 nm. The intrinsic superluminescence spectrum of the amplifier contained two spectral peaks corresponding to the quantum transitions from the ground and excited energy subbands [3, 10], whose amplitudes depended on the injection current. The halfwidth of the superluminescence spectrum at an injection current at which the spectral peak intensities became identical was 44 nm at an output optical power of 5 mW (Fig. 3). Detailed results of investigations of the spectral and power characteristics of such amplifiers can be found in [11].

Radiation in both modules was coupled in and out through a PANDA PM 850 polarisation-maintaining SMF. The light-emitting modules were assembled in butterfly housings and contained Peltier microcoolers and thermistors to stabilise the working temperature of active elements. The design of the light-emitting modules included cylindri-

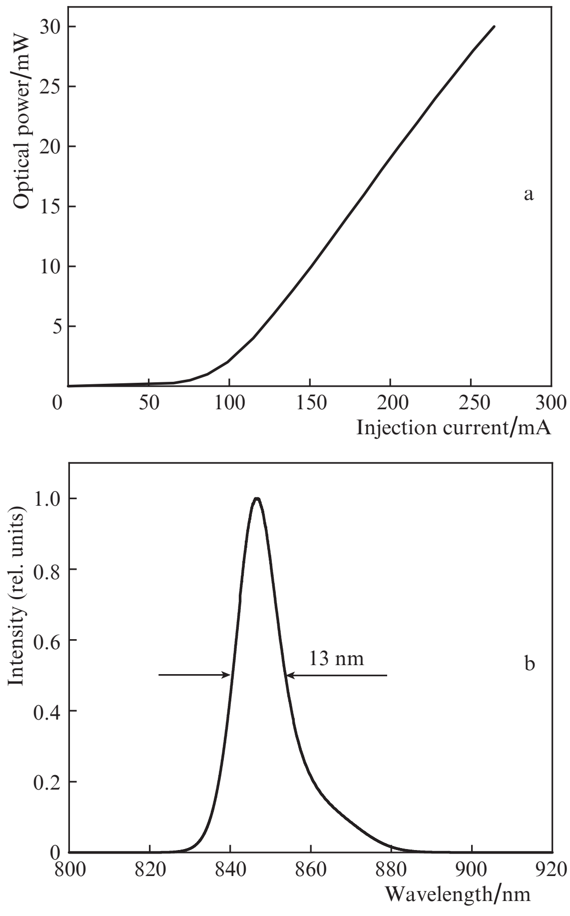

Figure 2. (a) Light–current characteristic of a commercial SLD-381 optical module and (b) its emission spectrum at an optical output power of 30 mW.

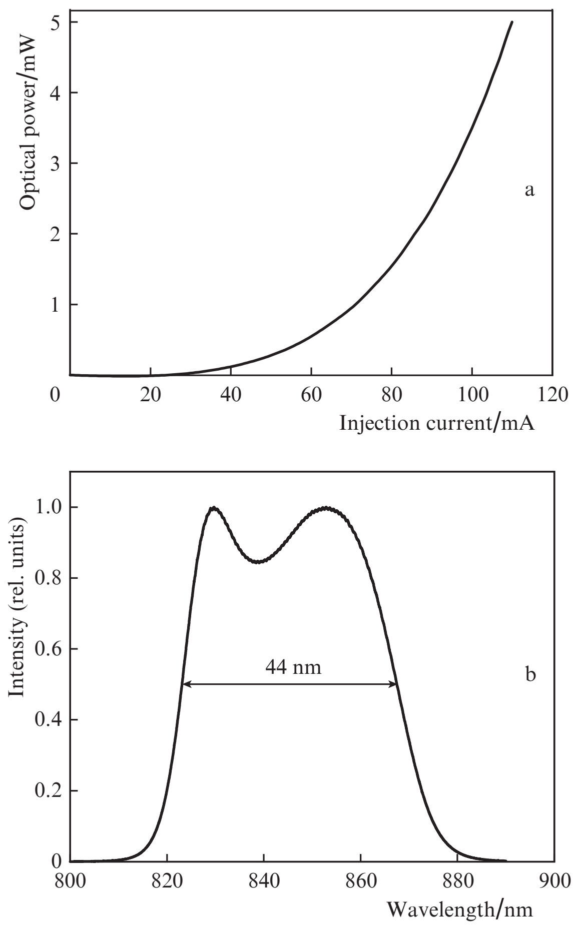

Figure 3. (a) Light–current characteristic of a SOA-372 optical module and (b) its spectrum at an injection current of 110 mA in the intrinsic superluminescence regime.

cal fibre micro-lenses with a bevelled face, and the axes of the active waveguides were inclined at an angle of 7° with respect to antireflection-coated output faces ($R \sim 10^{-4}$). This allowed us to achieve a low (not exceeding 0.5 %) level of intrinsic modulation power in the emission spectra of the modules. The coupling parameter of output SMFs was rather high (50 %–70 %).

As a spectrally selective element, which determined the width and profile of the output optical spectrum of the tandem source, we used a GR50-0310 ruled diffraction grating (Thorlabs) with a groove density of 300 lines mm^{-1}, which served as a single band pass filter with a bandwidth from 1 to 1.5 nm for wavelengths in the region of 850 nm. The filtration bandwidth was determined by the optical beam diameter and the number of diffraction grooves involved in diffraction, which depended on the angle of incidence of the beam on the grating. In the present work, the light beam diameter was 2.2 mm at a diffraction divergence of 0.5 mrad. The beam was formed by a fibre-optic collimator with an aspheric lens with a focal length of 11 mm, which was antireflection coated for the working wavelength region, because of which the level of reflected signals was no worse than –40 dB. The beam diffracted from the grating was directed to a similar fibre-optic collimator. The used pair of collimators was optimised at the stage of their fabrication to obtain the maximum transfer coefficient between them at a distance of 140 mm. The obtained transfer coefficient was 85 %.

To couple radiation into the output collimator, we used a compact plane metal mirror with a gold reflection coating (R = 98 %) and an outer protective dielectric coating, which was fixed in an adjustable mount. The use of the mirror makes it possible to minimise the angle α (see Fig. 1) between the incident and diffracted beams and thus to avoid excessive inclination of the diffraction grating, at which its point spread function would be noticeably narrower than 1.4 nm because the beam would overlap a large number of grating grooves. The use of high-quality optical mounts with precision alignment of rotation and swing angles for the mirror and the output collimator considerably simplified the procedure of radiation coupling into the output collimator and reduced it to only angular alignment of these elements. Tuning to the required wavelength was performed by rotating the diffraction grating around its axis. The maximum diffraction grating efficiency was 67 % at λ = 845 nm and the orthogonal orientation of the incident radiation polarisation vector to the grating grooves. For the used optical scheme geometry, the grating point-spread function width was 1.4 nm and the intensities of side lobes were below –40 dB (Fig. 4).

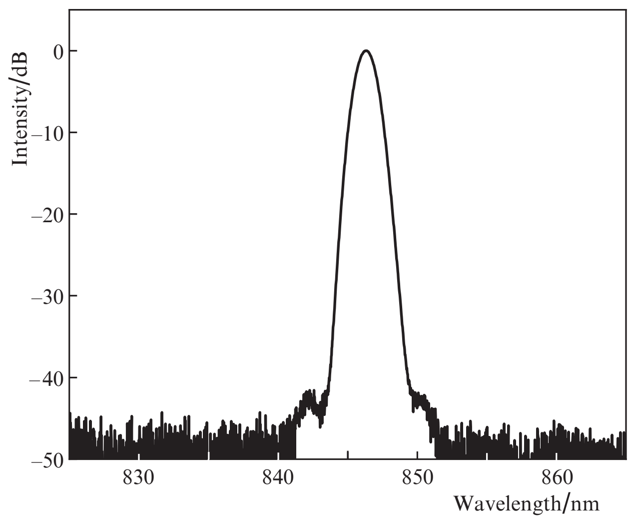

Figure 4. Optical spectrum of a light beam 2.2 mm in diameter reflected from the diffraction grating.

To eliminate parasitic optical coupling, a broadband fibre-optic isolator with low optical losses (below 1 dB) and an isolation ratio exceeding 30 dB was placed between the SLD and SOA. The extinction coefficient [10lg(P_{SL}/P_F), where P_{SL} and P_F are the powers along the slow and fast SMF axes] for the optical radiation at the isolator exit was rather high, namely, 25 dB. All fibre-optic elements of the scheme were based on PANDA polarisation-maintaining SMFs, whose slow axis was used as a working axis for the output radiation. The elements were connected in the optical scheme by sealing with precision orientation of the axes of optical fibres.

3. Power, spectral, and tuning characteristics of the light source

Figure 5 shows the dependences of the SOA optical output power on the injection current in the intrinsic superlumines-

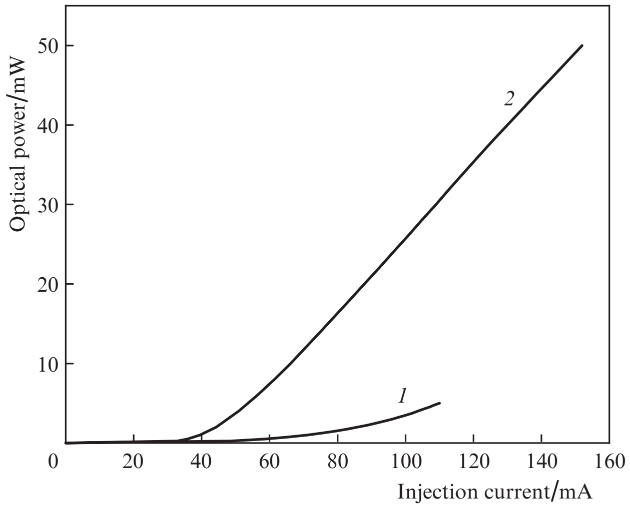

Figure 5. Light–current characteristic of the SOA (*1*) in the intrinsic superluminescence regime (without an input signal) and (*2*) in the regime of amplification of an input optical signal.

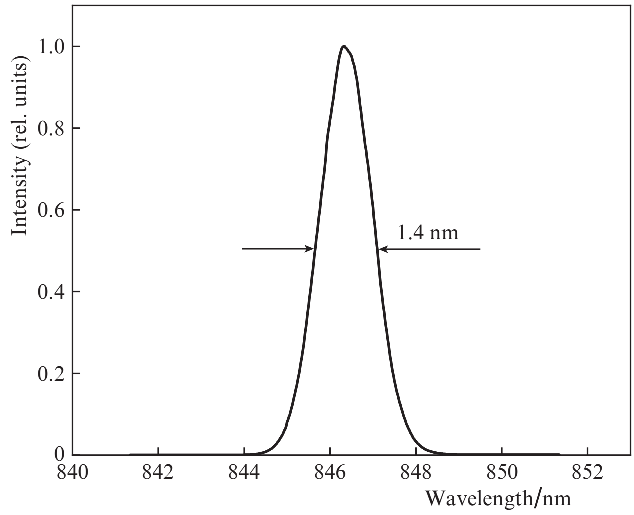

Figure 7. Spectral peak of an amplified optical signal (linear scale).

cence and signal amplification regimes. The use of a master SLD with a rather high (up to 2.5 mW nm^{-1}) spectral power density allowed us to obtain a 1-mW optical signal at the exit from the collimator placed behind the diffraction grating when the grating was tuned to the maximum of the SLD spectrum. At this optical signal incident to the SOA, the maximum amplified optical power in the output SMF was 50 mW at an injection current of 152 mA. Further increase in the optical power was limited by the optical breakdown threshold of the output face of the SOA active element and by the possibility of its irreversible catastrophic optical degradation.

As was shown in [11], an input optical power of 1 mW is usually enough for achieving a deep saturation of the SOA optical gain, at which the amplifier becomes weakly sensitive to backward optical reflections at the exit. Because of this, it is not necessary to use an output optical isolator, which allows one to save on expenses for its purchasing and installation. In addition, this eliminates the optical losses of the useful optical signal in the optical isolator, which vary from 25% to 40%, and, therefore, to achieve the maximum possible output power.

Spectral measurements showed that the peak intensity in the SOA spectrum exceeded the superluminescent pedestal by 30 dB at an output optical power of 50 mW (Fig. 6). The spectral peak profile (Fig. 7) exactly corresponded to the profile and width of the diffraction grating point-spread function. Numerical integration of the SOA output spectrum shown in Fig. 6 showed that 98% of the optical signal power is contained in the spectral peak and only 2% belong to the pedestal.

Figure 8 presents the envelope of the interference pattern visibility [autocorrelation function (ACF)], which was recorded using a high-resolution Michelson scanning interferometer. The central peak halfwidth corresponded to a coherence length of 0.45 mm. The measured coherence length sufficiently well corresponds to the calculated value for a Gaussian output spectrum [12]. In low-coherence interferometry applications, the intensity of the side lobes near

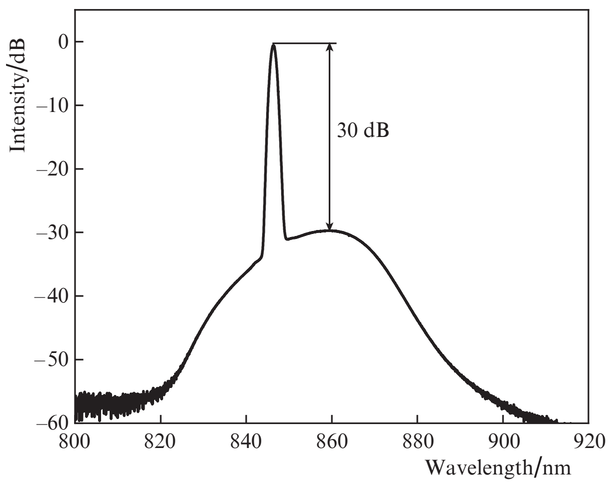

Figure 6. Spectrum of an amplified optical signal at an output SOA power of 50 mW.

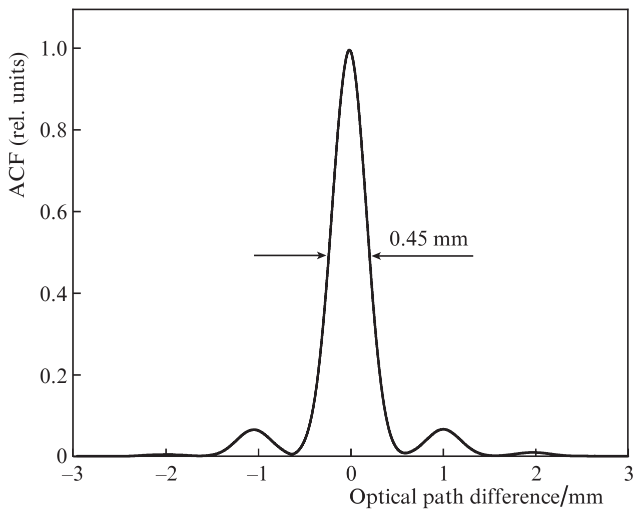

Figure 8. Envelope of the interference pattern visibility.

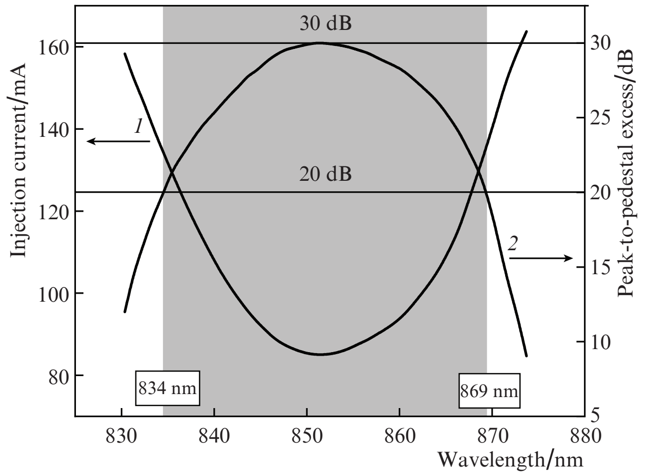

Figure 9. (*1*) Dependence of the SOA injection current on the wavelength of the input optical signal and (*2*) excess of the peak amplitude over the superluminescent pedestal in the SOA spectrum. Grey colour indicates the spectral tuning range at a more than 20-dB excess of the peak amplitude over the pedestal. The measurements were performed in the manual power control regime at an output optical power of 20 mW.

the central peak determines the signal-to-noise ratio and directly affects the quality of obtained images. The amplitudes of side lobes in our scheme were insignificant and did not exceed 7%–8% of the maximum. The presence of these peaks in the autocorrelation function is caused by deviation of the grating point-spread function from the ideal Gaussian shape.

The studied optical scheme of the light source was experimentally tested in the wavelength tuning regime with manual control of the SOA output power. Tuning was performed by rotating the diffraction grating with a step corresponding to a 1-nm change in the wavelength, and the manual control of the power was performed by setting the injection current of the SOA to a value at which the output optical power was 20 mW. The spectral tuning range in which the peak amplitude exceeded the superluminescent pedestal by at least 20 dB was 35 nm (grey region in Fig. 9). The peak width remained unchanged in the entire tuning range. If necessary, the tuning range can be increased by using a master SLD with a broader emission spectrum. However, this will inevitably decrease the output spectral power density of the SLD and, therefore, decrease the excess of the peak over the pedestal in the SOA spectrum. The choice of the optical modules (SLD and SOA) providing the best combination of the spectral tuning range and the excess of the peak over the pedestal directly depends on the requirements of a particular technical application.

An important working characteristic of any light source is the polarisation degree of its radiation. In the studied optical scheme, the ratio of optical powers along the output waveguide axes was 20:1, i.e., the polarisation degree was 90%. The polarisation degree at the entrance to the optical amplifier was very high (higher than 99%), and its decrease at the output of the scheme can be explained by an insufficiently high accuracy of spatial angular orientation of the output SMF with respect to the active channel of the SOA crystal. It is obvious that this parameter can be increased by using a SOA module with a more precise angular orientation of the output SMF.

It is important to note that the proposed optical scheme allows some optimisation of the spectral peak width by selecting the diameter of the beam incident on the diffraction grating and the number of grating grooves involved in diffraction. For example, simple replacement of the used optical collimator by a collimator with an output beam diameter of 1.2 mm in the same scheme geometry makes it possible to achieve a spectral peak width of 2.8 nm. The choice of the proper relation between the beam diameter and the number of diffraction grating grooves is directly dictated by the technical requirements of a particular practical application.

4. Conclusions

Our study sowed the practical possibility of fabricating a low-coherence light source with a high spectral brightness based on commercial SLD (SLD-381) and SOA (SOA-372) modules and a standard ruled diffraction grating with a groove density of 300 lines mm^{-1}. The light source with the proposed scheme experimentally demonstrated operation with an output spectral power density of 36 mW nm^{-1}, a wavelength tuning range of 35 nm (834–869 nm), and a more than 20-dB excess of the peak amplitude over the superluminescent pedestal.

It is shown that the central peak with a width of 1.4 nm in the optical spectrum has a smooth bell-shaped, close to Gaussian, profile with side lobes below the pedestal level (below –30 dB). The coherence length measured by the autocorrelation function (at half maximum) well corresponds to the value calculated for the Gaussian profile. The proposed optical scheme is universal, i.e., it can be reconstructed for application in other spectral ranges by simple replacement of optical units (SLD, SOA, optical collimators, diffraction grating). Changing such technical characteristics as the diameter of the optical beam incident on the diffraction grating, the number of grating groves, and the angle of incidence of a light beam on the grating, it is possible to moderately change the width of the spectral peak in the output spectrum. This allows one to optimise the spectral characteristics of the scheme for a particular practical application. In addition, it is possible to tune the position of the central spectral peak in the emission spectrum to a required wavelength by rotating the diffraction grating.

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