PACS numbers: 42.55.Px; 85.60.Jb
DOI: 10.1070/QE2009v039n09ABEH014091

Narrow-band double-pass superluminescent diodes emitting at 1060 nm

A.A. Lobintsov, M.V. Perevozchikov, M.V. Shramenko, S.D. Yakubovich

***Abstract*. Experimental data are presented which show that double-pass superluminescent diodes (SLDs) with fibre Bragg grating (FBG) based spectrally selective external reflectors offer emission linewidths in the range 0.1 – 1.0 nm, i.e., one to two orders of magnitude narrower in comparison with conventional SLDs and considerably broader in comparison with single-frequency semiconductor lasers. Their optical power at the single-mode fibre output reaches 5.0 – 8.0 mW, and can be raised to 50 mW using a semiconductor optical amplifier.**

Keywords: *superluminescent diode, semiconductor optical amplifier, single-mode optical fibre, fibre Bragg grating.*

1. Introduction

It is common practice to characterise the temporal coherence of a light wave by its coherence length, $L_{\rm coh}$. This quantity, corresponding to the optical path difference at which the visibility of an interference pattern drops twofold, is inversely proportional to the full width at half maximum (FWHM) of the emission spectrum, $\Delta\lambda$. For Gaussian spectral lines, we have

$$L_{\rm coh} = 0.44\lambda^2/\Delta\lambda = 0.44c/\Delta\nu, \quad (1)$$

where λ is the central wavelength; c is the speed of light; and $\Delta\nu$ is the FWHM of the spectral line in terms of frequency.

For laser diodes (LDs), the highest value of $\Delta\lambda$ is determined by the gain band width, which is typically tens of nanometres (several terahertz). It is such linewidths that are offered by superluminescent diodes (SLDs) – laser diodes with the lowest cavity fineness. Their coherence length, $L_{\rm coh}$, is in the order of 10 μm. The lower limit of $L_{\rm coh}$ is imposed by the achievable cavity fineness and the stability of the many factors that influence the shift and broadening of spectral lines. LDs with complex external cavity geometries for use in optical frequency standards and some basic research areas may have $\Delta\nu < 1.0$ Hz, which corresponds to $L_{\rm coh} > 10^5$ km. Thus, the range of achievable $L_{\rm coh}$ values covers more than 12 orders of magnitude. There are a variety of techniques for controlled broadening and narrowing of the spectral line of LDs [1], but the above $L_{\rm coh}$ range still has gaps which remain to be filled.

In particular, a number of spectroscopic and interferometric applications require sufficiently bright sources with linewidths from tenths of a nanometre to a few nanometres. Similar requirements are sometimes imposed on seed lasers of high-power solid-state and fibre laser systems. In the latter instance, amplitude modulation without spectral distortions is usually needed. One obvious way to achieve this $\Delta\lambda$ level is to combine SLDs with output spectral filters possessing the desired transmission (reflection) band. Unfortunately, this approach has limited effectiveness because only a small fraction (1 % to 10 %) of the SLD output power is utilised.

It is well known that, when a sufficiently strong, spectrally matched, narrow-band signal is fed to a semiconductor optical amplifier (SOA), its output spectrum is dominated by photons in the frequency band of the input signal. In the case of gain saturation, the brightness of the corresponding spectral peak may be three to four orders of magnitude higher than that of the superluminescent pedestal [2]. A similar effect is observed for double-pass SLDs if their external reflector possesses spectral selectivity. In this work, fibre Bragg gratings (FBGs) are used as such reflectors, which can be inscribed so as to ensure the desired characteristics of the reflection spectrum with high accuracy [3].

2. Experimental samples

We used single-pass SOAs with a peak gain wavelength near 1060 nm, utilising InGaAs/GaAlAs/GaAs double quantum well heterostructure active elements, described in detail elsewhere [4, 5]. The SOAs were housed in butterfly packages with two types of input/output single mode fibre (SMF) pigtails: Corning Pure Mode 780 (isotropic) and Corning PANDA 850 (polarisation-maintaining). Bragg gratings with a resonance wavelength near 1063 nm were UV written into the SMFs by a frequency-doubled argon laser (244 nm) using two-beam interference [6]. The peak reflectance was about 5.0 %. This value was selected as a trade-off between sufficiently high spectral selectivity of the reflectors and sufficiently high parasitic-lasing threshold of the double-pass SLDs, related to the nonzero residual reflectance of their output facets. The FWHM of the FBG reflection band, $\Delta\lambda_{\rm FBG}$, ranged from 0.5 to 3.0 nm.

A.A. Lobintsov, M.V. Perevozchikov, M.V. Shramenko Superlum Diodes Ltd., POB 70, 117454 Moscow, Russia;
S.D. Yakubovich Moscow State Institute of Radio-Engineering, Electronics and Automation (Technical University), prosp. Vernadskogo 78, 117454 Moscow, Russia;
e-mail: yakubovich@superlumdiodes.com

Received 24 February 2009
Kvantovaya Elektronika **39** (9) 793 – 796 (2009)
Translated by O.M. Tsarev

The above spectral parameters of the FBGs were measured using a BroadSweeper-1060-01 tunable laser. A prototype of this source, with a similar SOA as an active element and an acousto-optic tunable filter in its external fibre cavity, was described in a previous report [5]. The final version has the following performance parameters:

Central wavelength/nm	1060
Output power/mW	
LOW regime	1.0
HIGH regime	5.0
Maximum wavelength tuning range/nm	
LOW regime	65
HIGH regime	60
Line width (FWHM)/nm	0.05
Degree of polarisation (%)	>98
Side-mode suppression (SMS)/dB	55

Spectral tuning can be performed manually in 0.05-nm or larger steps, or in linear sweep mode at a rate of up to 10^4 nm s^{-1}. In addition, it is possible to switch between two preset wavelengths at a specified frequency. In all the tuning modes, the automatic output power control system maintains the power with a stability of about 1 %.

Figure 1 shows the transmission spectrum of one of our FBG samples, measured in 0.2-nm steps. From such spectra, the main parameters of the FBG reflection band can be determined with sufficient accuracy. The reflection spectra of strictly periodic FBGs are known to contain sidelobes, which are weaker than the main lobe by an order of magnitude or more [3]. The measurement procedure we used was not accurate enough to detect sidelobes. At the same, these were well defined in the output spectra of the double-pass SLDs (see below).

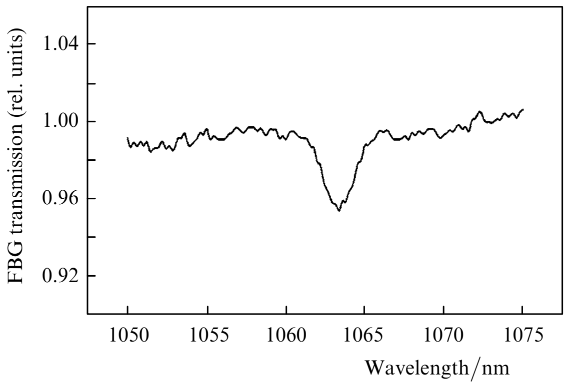

Figure 1. FBG transmission spectrum measured using a BS-1060-01 tunable laser.

Sections of the SMFs having Bragg gratings were fusion-spliced to one of the SOA's fibre pigtails using a Fujikura FSM-40F welding device. The fusion splice loss was within 0.1 dB. The measurements were made using cw injection, and the SOA was temperature-stabilised at 25 °C.

3. Experimental results

Figure 2 shows the light – current characteristics of SLDs in the conventional single-pass configuration and in a double-pass design. The FBG reflector increases the external quantum efficiency of the device by a factor of 1.5 – 2.0 and severely transforms its output spectrum (Fig. 3). The spectrum shows a narrow peak, much stronger than the superluminescent pedestal. The FWHM of the peak, $\Delta\lambda_c$, is determined by the reflection band of the FBG and the gain of the SOA (pump power). In addition to the main peak, there are sidelobes, due to the above-mentioned sidelobes in the FBG reflection spectrum. By analogy with lasers, the difference in intensity between the main peak and sidelobes will be referred to here as SMS. With increasing injection current, the FWHM of the peak decreases, while the SMS rises, with a steeper slope at smaller $\Delta\lambda_{FBG}$. The plots for $\Delta\lambda_{FBG} = 3.0$ and 0.5 nm are presented in Fig. 4. One can in principle fabricate aperiodic FBGs that would have reflection spectra free of sidelobes [7, 8]. Such FBGs might ensure a marked increase in SMS. However, writing such gratings requires the fabrication of an expensive, precision phase mask, which is warranted only in the case of commercial-scale production.

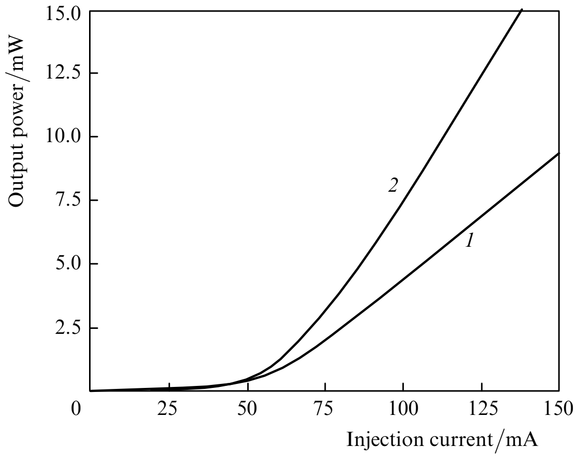

Figure 2. Light – current characteristics of an SOA (*1*) in a single-pass SLD design and (*2*) in a double-pass SLD design with an FBG reflector.

It is known that even conventional single-pass SLDs, with the maximum reflection suppression at both ends of the active channel, are rather sensitive to parasitic feedback effects [9]. With the input/output coupling efficiency in the SOA taken into account, the effective reflectance of the FBGs in our samples is near 1 %, which is about two orders of magnitude greater than that of the facets of conventional SLDs. For this reason, the double-pass SLDs under investigation are very sensitive to stray reflections of the output beam and, in practical applications, should be used with output optical isolators. Fortunately, as distinct from visible and near-IR isolators, 1060-nm fibre-optic isolators are relatively inexpensive, miniature devices. However, even in the absence of external feedback, at a sufficiently high optical gain (injection current) the double-pass SLDs are prone to 'sluggish' parasitic lasing because of the above-mentioned residual reflection from their output facets. This produces no breaks in their light – current characteristics, but the central peak in their output spectrum becomes rugged instead of being bell-shaped. The parasitic-lasing threshold of our samples was 80 – 95 mA, and the output power at which their emission spectra remained smooth reached 5 – 8 mW. Therefore, such emitting modules may be of practical use.

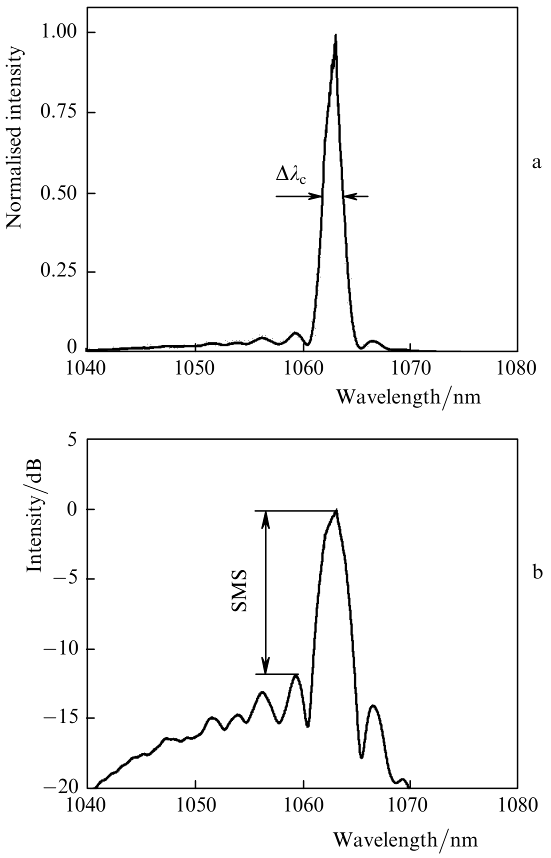

Figure 3. Output spectrum of a double-pass SLD ($\Delta\lambda_{FBG} = 1.5$ nm, $I = 80$ mA): (a) linear scale, (b) logarithmic vertical axis.

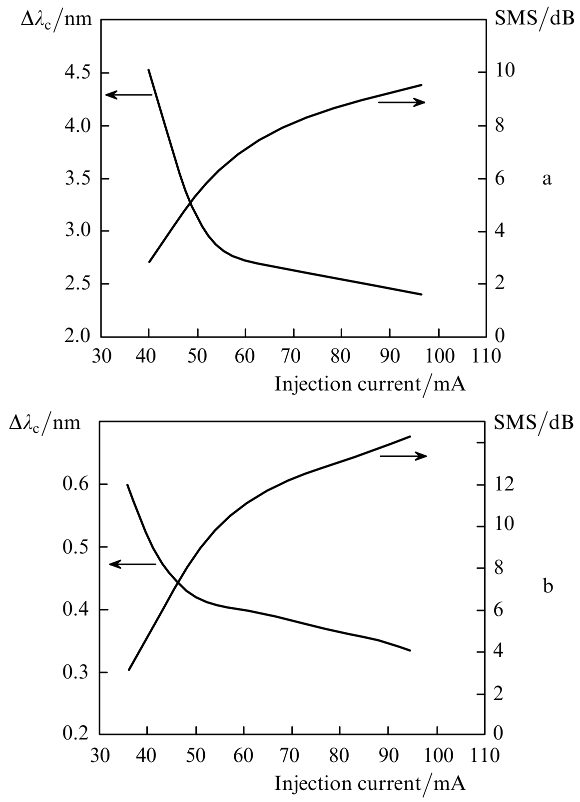

Figure 4. FWHM of the main peak, $\Delta\lambda$, and difference in intensity between the main peak and sidelobes, SMS, as functions of injection current for double-pass SLDs with $\Delta\lambda_{FBG} = 3.0$ (a) and 0.5 nm (b).

In a number of technical applications, considerably higher output powers are required. For example, according to experts from Continuum Inc., one of the high-power Nd : YAG laser systems under development requires a low-noise 1063-nm seed source with a linewidth of 0.3 nm and an SMF output power of 30 mW. Clearly, to solve this problem an additional SOA must be used as an output amplifier, i.e., a master oscillator/power amplifier (MOPA) system must be built. The double-pass SLD serving as a master oscillator may then operate under moderate pumping, well below the parasitic-lasing threshold.

The block diagram of such a device is presented in Fig. 5. We tested two laboratory-produced prototype MOPA systems, with narrow- and broadband FBGs. The output characteristics of the corresponding master oscillators (FBG and SOA1) are presented in Fig. 6. All the optical connections were made with a polarisation-maintaining SMF. The forward loss due to the PMIS10P fibre-optic isolator was about 1.5 dB, and the backward loss was above 30 dB. Both SOAs were energised and thermally stabilised by a PILOT-4 controller. If necessary, SOA2 can serve as an amplitude modulator. A modified model of the controller must then be used, which ensures the required pulsed injection mode.

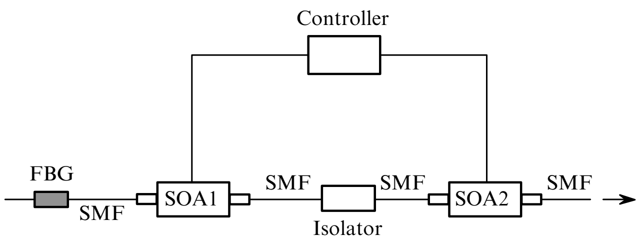

Figure 5. Schematic diagram of the MOPA.

As mentioned above, cw pumping of both SOAs was used in our measurements. Figure 6 shows the main output characteristics of the prototype MOPA systems as functions of the injection current through SOA2. In both instances, the input power (at the input of the optical isolator) is 4.0 mW. With increasing injection current, the output power increases steadily. This study was limited to a level of 50 mW, which corresponded to a power density on the output SOA facet near 2×10^6 W cm^{-2}. This is about half the highest achievable level, determined by SOA overheating. Note that no catastrophic optical damage of the devices was detected. With increasing injection current, the FWHM of the central peak ($\Delta\lambda_c$) and the SMS value, both determined by the input signal spectrum, rapidly reach a maximum and then remain roughly constant at 2.0 nm and 13 dB for $\Delta\lambda_{FBG} = 3.0$ nm and at 0.3 nm and 15 dB for $\Delta\lambda_{FBG} = 0.5$ nm.

One spectral characteristic of practical importance is the fraction of output power in the central peak:

$$K_s = \int_{\lambda_c-\Delta\lambda_c}^{\lambda_c+\Delta\lambda_c} S(\lambda)\mathrm{d}\lambda \Big/ \int_{-\infty}^{+\infty} S(\lambda)\mathrm{d}\lambda, \qquad (2)$$

where $S(\lambda)$ is the spectral distribution of the output intensity and λ_c is the central wavelength.

The input signal had $K_s \sim 0.7$ at $\Delta\lambda_{FBG} = 3.0$ nm and $K_s \sim 0.4$ at $\Delta\lambda_{FBG} = 0.5$ nm. At the MOPA output, K_s was

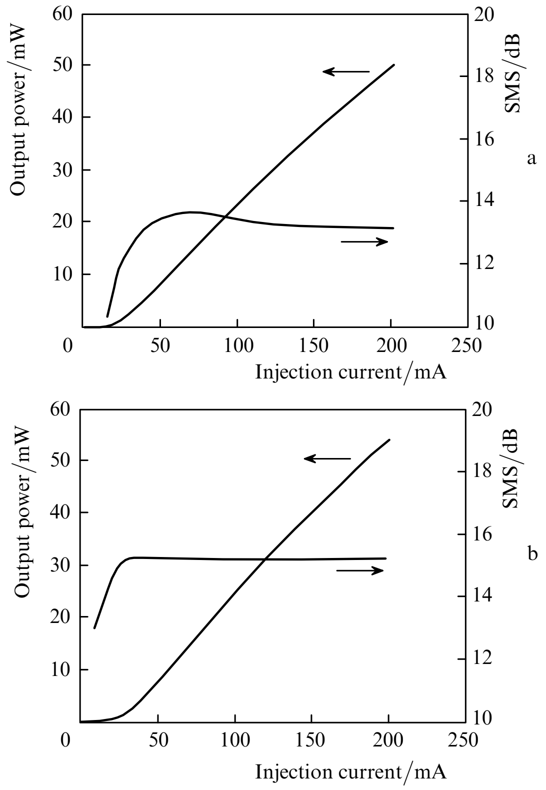

Figure 6. Output characteristics of the MOPA systems containing master oscillators (double-pass SLDs) with $\Delta\lambda_{FBG} = 3.0$ (a) and 0.5 nm (b).

~ 0.90 and ~ 0.65, respectively, indicating that most of the output power was concentrated in the narrow central peak.

One important advantage of the device under consideration is its low sensitivity to optical feedback, which is due to the strong gain saturation in the output SOA in its operating range. Stray feedback may influence the output power or distort the output spectrum, but causes no degradation of the SOA. In view of this, no output optical isolator is needed.

4. Conclusions

The present experimental results show that the use of FBGs as spectrally selective reflectors enables the fabrication of narrow-band SLDs whose emission spectrum has a width determined by the reflection band of the FBG. The SLD modules produced in this study have a central wavelength of 1063 nm and an FWHM of the gain spectrum from 0.3 to 2.0 nm. The cw power at the SOA output reaches 5.0 – 8.0 mW. The use of an appropriate SOA allows these parameters to be raised by an order of magnitude or more.

The proposed approach can be used as well in other spectral regions for which sufficiently efficient SLDs (SOAs) are available. Amplitude modulation of the output of such devices requires further investigation. The time constant of SLDs and SOAs used as amplitude modulators is, in principle, ~ 1.0 ns, but the microwave characteristics of particular modules usually severely limit this parameter.

Acknowledgements. We are grateful to A.T. Semenov for his continuous interest in this work. This work was supported in part by the Federal Agency for Education (Project No. 2.1.1.195).

References

1. Deninger A., Renner T. *Opt. Laser Eur.*, **162**, 30 (2008).
2. Shramenko M.V., Andreeva E.V., Mamedov D.S., Shidlovsky V.R., Yakubovich S.D. *Proc. SPIE Int. Soc. Opt. Eng.*, **6079**, 275 (2006).
3. Vasil'ev S.A., Medvedkov O.I., Korolev I.G., Bozhkov S.A., Kurkov A.S., Dianov E.M. *Kvantovaya Elektron.*, **35** (12), 1085 (2005) [*Quantum Electron.*, **35** (12), 1085 (2005)].
4. Lapin P.A., Mamedov D.S., Marmalyuk A.A., Padalitsa A.A., Yakubovich S.D. *Kvantovaya Elektron.*, **36** (4), 315 (2006) [*Quantum Electron.*, **36** (4), 315 (2006)].
5. Lobintsov A.A., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **38** (7), 661 (2008) [*Quantum Electron.*, **38** (7), 661 (2008)].
6. Medvedkov O.I., Korolev I.G., Vasil'ev S.A. Preprint No. 6 (Moscow: A.M. Prokhorov General Physics Institute, RAS, 2004).
7. Albert J., Hill K.O., Malo B., Theriault S., Bilodeau F., Johnson D.C., Ericson L.E. *Electron. Lett.*, **31**, 222 (1995).
8. Erdogan T.J. *Lightwave Technol.*, **15**, 1277 (1998).
9. Andreeva E.V., Shramenko M.V., Yakubovich S.D. *Kvantovaya Elektron.*, **37** (5), 443 (2007) [*Quantum Electron.*, **37** (5), 443 (2007)].